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# THE ORDOVICIAN-SILURIAN BOUNDARY IN BRITAIN AND NORTH AMERICA

OWEN THOMAS JONES
Victoria University of Manchester

ABSTRACT

The difficulties experienced in correlating strata near the Ordovician-Silurian boundary in Britain and North America arise partly from imperfect descriptions of the British Llandovery fauna. Many characteristic Llandovery fossils are attributed in lists to the Bala or Wenlock. In Britain, Ordovician and Silurian rocks occur in three facies: (1) pelitic, (2) psammitic, and (3) calcitic facies.

The better-known American Ordovician and Silurian rocks belong mainly to the calcitic facies.

A comparison is made between the genera of brachiopods and trilobites recorded from the British and American rocks near the Ordovician-Silurian boundary. In Anticosti, the English Head, Charleton, and Ellis Bay must be referred to the Bala; the Becsie River is probably Lower Llandovery, while the Gun River, Jupiter River, and Chicotte are Upper Llandovery. The Richmond of the interior states is unmistakably Bala; the Clinton (and probably the Medina) is Upper Llandovery. Evidence that Lower Llandovery rocks occur on the American continent is wanting.

Ulrich, in a paper contributed to the Twelfth International Geological Congress at Ottawa in 1913 on the Ordovician-Silurian boundary, comments on the difficulty which American geologists have experienced in correlating certain formations lying near this boundary with the divisions established in Great Britain. As one instance of the cause of uncertainty in interpreting the British formations, he quotes from the last edition of Geikie's *Textbook* a list of fossils which are said to be found associated with regular Ordo-

vician types, and notes that in "America none of these generic and specific types occurs beneath the Richmond and most of them are never seen beneath the Upper Medina or the Clinton." The justice of much of this and other criticism in the same paper must with regret be admitted, though, as explained below, the writer is obliged to join issue with certain other statements by the same author.

### CAUSES OF UNCERTAINTY IN CORRELATION

The causes of the uncertainty in interpreting the British successions and faunas abroad are various, and one of them can be traced a long way back to the date of publication of Murchison's *Silurian System* (1839), wherein, owing to an unfortunate error, that author included the rocks now known as the Upper Llandovery with the totally distinct Caradoc (or Bala) formation as Caradoc sandstone, both being assigned to the Lower Silurian. Many fossils now regarded as characteristic of the Silurian rocks (Upper Silurian of Murchison) were thus figured along with others which are equally characteristic of the Ordovician (Lower Silurian in part). This had the effect of masking the essential faunal differences between these two systems, and led to the belief that the Silurian system was one great homogeneous whole. This stratigraphical error was detected some years later by Sedgwick and McCoy, and when a great discordance was proved by Aveline and Salter to occur within the Caradoc sandstone, Murchison created the Llandovery formation for certain rocks, which intervened between the redefined Caradoc and the base of the Wenlock. He maintained that this formation in its upper part showed affinities with the Wenlock, and in its lower part with the Caradoc formation, thus bridging over the gap between the two halves of the Silurian, and uniting them into one grand system.

Subsequently for various reasons Lapworth, Lyell, Hicks, and Hughes proposed that the base of the Upper Silurian should be drawn at the base of the Llandovery, a proposal which has now gained general acceptance, and is adopted on the recent maps of the Geological Survey. In the Llandovery district, however, which has not been revised by the Survey, only the Upper Llandovery is separately mapped, the Lower Llandovery being still colored as Lower Silurian, though the sparsely scattered letter *b4* indicates that in

those localities Lower Llandovery rocks had been recognized. The most important evidence for regarding the whole of the Llandovery as part of the same great system as the Wenlock and Ludlow was contributed by Lapworth from his study of the distribution of the graptolite faunas of Britain and elsewhere. Lapworth also proposed the name Valentian as a general equivalent to the Llandovery formation of some authors. The history of the Valentian series was recently reviewed by the writer.[1]

Another cause of uncertainty in interpreting the British succession was the prolonged controversy between Sedgwick and Murchison and their respective adherents regarding the mutual relations and limits of the Cambrian (Sedgwick) and Silurian (Murchison) systems. Lapworth proposed as a compromise the name Ordovician, and this term is now generally adopted for many of the rocks which were originally described by Murchison as Lower Silurian, the name Silurian being now restricted to the original Upper Silurian divisions, Wenlock and Ludlow, together with the later-established Llandovery. In spite of the fact that the term Ordovician was steadily gaining acceptance among British geologists, and is now adopted by the Geological Survey of Great Britain, there is no doubt that the varying use of the term Silurian in this country proved extremely confusing, especially to those who were not well acquainted with the British rocks. Accordingly, De Lapparent proposed to replace the name by "Gothlandian." Whatever may have been the position previously, there has been no serious justification within the last few years for this change of name. The Silurian succession of "Siluria" is undoubtedly more complete than in Gothland, and its relations to older and newer strata are at least as clear, so that the substitution of "Gothlandian" for "Silurian" seems both unnecessary and even undesirable in that it can only lead to further confusion.

A third source of difficulty in correlation arises, it must be admitted, from the general neglect by British paleontologists of the shelly faunas of the Lower Paleozoic. The descriptions of most of the typical successions and of the characteristic fossils are old and inadequate, though this defect is now being rapidly remedied. The

[1] *Quart. Jour. Geol. Soc.*, Vol. LXXVII (1921), pp. 144–74. This paper contains numerous references.

predominant element in the faunas is the Brachiopoda, yet Davidson's monograph of the Silurian brachiopods was until recently almost the only work of reference on this group. Apart from errors, many of which were unavoidable, it is clear that Davidson allowed himself far too great a latitude in the interpretation of species, so that numerous forms which are now known to be characteristic of restricted horizons were ignored, or represented as examples of the high degree of variation exhibited by certain species. Further, owing to the late recognition of the Llandovery formation, the majority of the brachiopods that were figured were derived from Wenlock or Bala (Caradoc) rocks. Such brachiopods as were figured from the Llandovery were generally loosely assigned to Wenlock or Caradoc species, which were better known because they were more abundantly represented in collections. Endeavors were made by Salter, McKenny Hughes, Marr, and others to draw up authentic lists of Llandovery fossils, but owing to imperfect knowledge of the distribution of that formation, these lists contain numerous errors, and it is still unfortunately the fact that in many British museums a considerable number of typical Llandovery fossils remain in the cases assigned to the Bala or Caradoc faunas.

For these and other reasons, lists of British Lower Paleozoic fossils appear to contain a very high proportion of forms which have a wide range in time. *Dalmanella elegantula*, *Atrypa reticularis*, *Leptaena rhomboidalis*, *Plectambonites sericeus*, *Calymene blumenbachi* may be enumerated as examples. The Ordovician and Silurian Brachiopoda of Girvan (Scotland) have been described recently by Reed, who has also at various times contributed notes and descriptions of new species from Lower Paleozoic formations, while the graptolite faunas are well known through the researches of Lapworth, Elles, and Wood (Shakespear). A large amount of work still remains to be done, however, before the Ordovician and Silurian faunas of Britain and especially those of the Llandovery are adequately described and illustrated.

It may, therefore, serve a useful purpose at this stage to review certain elements of these faunas with a view to defining which forms have been found by experience to be characteristic of the British Ordovician and Silurian systems, and by this means to attempt a

correlation with the British succession of certain American faunas which lie near the junction of these two systems.

## SEDIMENTARY FACIES OF BRITISH ORDOVICIAN AND SILURIAN ROCKS

In Britain, both the Ordovician and the Silurian rocks are developed in three more or less distinct sedimentary facies, which correspond to differences in the conditions of deposition. These facies, as will be shown below, do not strictly correspond to the faunal facies.

*Pelitic facies.*—One facies, which will be denoted the pelitic facies, is represented by dark-blue or gray shales in which the fauna is mainly graptolitic. These shales are usually of small thickness, but contain many bands crowded with a great variety of graptolite forms, and the faunal assemblage of these bands is in general sufficiently distinct to allow the strata to be grouped into zones. A noteworthy feature of these zones is their extraordinary persistency, so that it is possible to recognize by means of its graptolite fauna a given thin band of shale at localities nearly 100 miles apart. Further, it is even possible in favorable circumstances to identify a band a fraction of an inch in thickness in two localities equally distant, as, for instance, the "green streak" first noted by Marr and Nicholson in the band with *Monograptus argenteus* in the Lake District and subsequently identified in the equivalent band in central Wales. Stratification and often lamination planes are well marked and occur at intervals of a few inches. The succession is, so far as can be seen, complete, and deposition of fine muds appears to have been continuous through long periods.

*Psammitic facies.*—The second or psammitic facies is represented by a much greater thickness of mudstones, sandy mudstones, and occasional conglomerates, all these deposits being imperfectly sorted and grading into one another. Stratification planes are often indistinct and usually occur at intervals of several feet. Thin beds of limestone may occur sporadically, but form an insignificant proportion of the deposits. The fauna may be almost wholly graptolitic on one margin, almost wholly shelly on the other, while in between these faunas may alternate in the vertical succession. On faunal

grounds this facies can generally be divided into distinct subfacies. Physical and faunal breaks may sometimes be detected, which may or may not be accompanied by beds of conglomerate. These visible breaks tend to increase (within limits) in number and importance from the graptolitic margin toward the shelly margin of this facies, and it may be inferred that in the former, deposition was almost, if not quite, continuous in a steadily subsiding region, while in the latter, periods of steady subsidence alternated with stationary periods, or were even interrupted by emergence and erosion.

*Calcitic facies.*—In the third or calcitic facies there is a greater variety of deposits. One common type consists of well-sorted coarse or fine sands, now consolidated into sandstones, fairly free from mud. These sandstone beds may alternate with beds of shale or mudstone, these different beds being sharply defined. Calcareous matter is often abundant, either forming beds or lenticles of limestone, or serving as the cement of the sandstones and shales. Another type is represented by beds of limestone, usually argillaceous and frequently nodular. The beds are, in general, only a few inches in thickness, and individual beds are separated from their neighbors by sharply defined planes. More commonly, beds of shale or marl intervene between the limestones, and there is rarely any gradation from a limestone bed to the overlying shale. In most cases the shale or marl can be readily peeled off, revealing the upper surface of the limestone on which it rested. In such cases, this surface usually bears abundant shelly fossils, such as brachiopods, trilobites and Bryozoa, the upper sides of which project above the general surface of the limestone, but are firmly attached to that rock on their lower sides. This facies may be associated with deposits of shale of considerable thickness and of uniform texture. A feature which these types have in common is the evidence they present that the area of deposition was frequently swept by strong currents which removed the finer material elsewhere. At other times the finest mud settled over the floor of the sea.

The thickness of the deposits is variable, but is usually small as compared with that in the psammitic facies. The fauna is almost exclusively shelly and is usually prolific. The assemblage of organisms in one bed or in a group of beds of limited thickness is often markedly

different from that in adjoining beds or groups of beds, and the same assemblages can sometimes be recognized in the same stratigraphical order in many localities. The physical and faunal characteristics of this facies lead to the supposition that sedimentation was frequently interrupted for intervals of unknown length, and that the apparently comformable succession may conceal many and perhaps important discontinuities or disconformities.

### DISTRIBUTION OF FACIES

The geographical distribution of these facies in Britain is related to the position of the shore lines of the Ordovician and Silurian seas. As was first pointed out by Lapworth, the Ordovician and Silurian rocks were deposited in a subsiding troughlike basin ranging northeast and southwest. This basin was probably bounded on the northwest by the area now forming the Highlands of Scotland, and on the southeast by a low-lying land mass which extended for the greater part of these periods over the English Midlands. The Highland land mass probably suffered repeated elevation, while the Midland mass remained relatively stationary or subsided slowly with intervals of rest or of emergence.

The calcitic facies was deposited near the land masses, but was most extensive near the Midland land area. The sea in which it was laid down appears to have extended over a stable platform and was of the nature of a shallow epicontinental sea in which the physical conditions approached at times those of existing lagoon areas.

The psammitic facies was laid down farther from the coast line near the margin of the stable platform in an area which was subjected to almost uninterrupted downward warping. Such interruptions in the warping process as occurred affected mainly the shoreward margin of the facies, and their effects died away seaward. The steady subsidence combined with the nearness of the area to the source of supply of the sediments afforded favorable conditions for the accumulation of a great thickness of strata. The massive character of the beds and the almost complete absence of sorting of sediments point to rapid deposition and a general absence of strong currents.

The pelitic facies is confined to the central or axial area of the

basin. Although the view has been frequently expressed that this facies was deposited in a deep sea, the writer is unable to subscribe to this view. The well-marked stratification and lamination of the shales and the frequent occurrence of inclined bedding or "drift bedding" (Sorby) in some of the sediments seem to indicate deposition at relatively shallow depths. Their physical characteristics and small aggregate thickness are due in the main to the fact that the bulk of the sediments had been deposited nearer the land and only the finest materials reached the central area.

The pelitic facies is represented by the Glenkiln-Hartfell (Bala) and Birkhill (Valentian) shales of the southern uplands of Scotland, the Stockdale (Valentian) shales of the Lake District, a part of the succession near Bala, most of the Lower and some of the Upper Valentian of north and central Wales, and the *Dicranograptus* (Bala) shales of south Wales. In Wales the transition from this facies to the psammitic facies can be traced very clearly in both the Bala and the Valentian rocks.

The psammitic facies is represented by the Ordovician and Silurian rocks of Girvan in southwest Scotland, the Upper Valentian and higher Silurian of the southern uplands of Scotland, the Wenlock and Ludlow (or Salopian) rocks of the Lake District, the Bala succession east of Bala, recently described by Dr. G. L. Elles, the Bala and Llandovery rocks extending at intervals from the Berwyn Hills east of Bala southward to Llandovery; also the Upper Bala and Llandovery rocks of Haverfordwest in Pembrokeshire. The Wenlock and Ludlow (or Salopian) rocks of north and central Wales, and extending from Builth to Llandeilo in south Wales, pertain to the same facies.

The calcitic facies is not now represented in the south of Scotland, but is partly represented in the Lake District by the Coniston limestone series (Caradocian and Ashgillian). The classic sections of Murchison in the Caradoc and Silurian rocks of Shropshire belong in the main to this facies, which extends from there eastward to the neighborhood of Birmingham and southward through Woolhope, May Hill, and the Malvern Hills to Tortworth in Gloucestershire. It is partly represented also in south Pembrokeshire at Marloes Bay and south of Haverfordwest, though in these southern dis-

tricts it appears to be transitional to another psammitic facies which probably pertains to another area or province of deposition represented mainly on the continent of Europe. A pelitic facies of this same province, or a transition from the psammitic facies, has been found in deep borings in the southeast of England. It is doubtful whether the Midland land mass extended far southward, though it probably extended northeastward under a part of the Pennine Chain. It will be noted that in one and the same region the pelitic facies was developed in one period, the psammitic or the calcitic in other periods. These changes must undoubtedly be correlated with shifting of the strand line due to movements of the crust.

### ZONING BY FOSSILS

It is usually not difficult by careful collecting in strata which pertain to the pelitic or to the calcitic facies to establish subdivisions based upon the distribution of certain organisms. Many species are confined to certain narrow bands, and the assemblages can often be recognized in localities many miles apart. This was accomplished for the rocks of the pelitic facies by Lapworth many years ago, and his method of zoning by means of graptolites has been followed with conspicuous success by many workers among these strata in Britain and Scandinavia. The same method can also be applied to the calcitic facies, using for the purpose brachiopods and trilobites, which form the dominant elements in the fauna. The success of graptolite-zoning arises from the remarkably complete record of sedimentation which these rocks present and the wide distribution of these organisms and their relatively rapid change with time. The sharp changes of fossil assemblages which are observed among rocks of the calcitic facies, which make it possible to apply zonal methods, seem, however, to arise from the incompleteness of the stratigraphic record due to oft-repeated interruptions of sedimentation.

To apply zonal methods to the thick accumulations of the psammitic facies is a much more difficult problem. In these rocks fossils are not so abundant in proportion to the mass of the rock, and it requires diligent collecting from a great thickness of strata to obtain a representative fauna. Changes in the fauna in the vertical succession are less conspicuous, and most of the species range through a

considerable thickness of strata. Even where a certain species occurs in a well-defined band, the same or apparently the same species may recur in another band or bands hundreds of feet higher in the succession, while so far as can be discovered, it is absent from the intervening strata. It is, therefore, a matter of considerable difficulty to establish in the psammitic facies zonal subdivisions based on the distribution of shelly fossils, and even when they have been established in one area, their recognition in another area is often attended with uncertainty.

### COMPARISON OF BRITISH AND AMERICAN ORDOVICIAN AND SILURIAN

The characteristics of the British Ordovician and Silurian rocks have been described in some detail, as they appear to differ in some essential respects from most of the American rocks of the same ages, and, as Ulrich[1] states, "local environment of observers is a more potent factor in the shaping of their opinions than one would ordinarily believe." There is little doubt that certain statements by that author regarding the relative completeness of the record furnished by the Ordovician and Silurian rocks of Britain and America follow from the fact that his experience, great as it undoubtedly is, has been derived mainly from the study of the American lithological and faunal succession. The insistence by American writers on repeated stratigraphic and faunal breaks in the succession and on the occurrence of "lenses" of certain faunas which are unknown elsewhere, together with the lithological character of the strata, seem to imply that the greater part of the Ordovician and Silurian rocks of North America belong to the calcitic facies as defined above, and it is only in the island of Anticosti that any approach to the psammitic facies may be observed, though even there it is not typically developed. It is significant that in that island the succession appears to be much more complete than in the interior areas of the continent. Accordingly, difficulty was experienced in delimiting faunal groups and formations owing to the existence of "long-ranging species," and the uncertainty caused by recurrence of species was encountered, as is usually the case in working on rocks of the psammitic facies. On

[1] *Op. cit.*, p. 19.

these grounds there is little doubt that, except possibly near the base of the Ordovician, the British succession of Ordovician and Silurian rocks bears comparison in point of completeness with the succession in any other country.

The extraordinary extent of the calcitic facies in America as compared with Britain probably accounts for a striking difference in the general character of the faunas on the two sides of the Atlantic, viz., the abundance and variety of the bryozoan and coral fauna in America and the poverty of the British rocks in these organisms. Some of the differences may be more apparent than real, since the preservation of these organisms in the British rocks is often such that specific or even generic identification is impossible. Even making allowance for this as a partial explanation, there is little doubt that conditions were more favorable in America for the existence of these organisms. On the other hand, the British trilobite fauna, especially of the Ordovician, is far more varied than that of the American rocks, though fortunately there are many genera in common. One must for the present rely mainly upon brachiopods and trilobites in instituting a comparison between the faunas of the two countries. It is hardly to be expected that many species of either of these groups will be common to the rocks of such distant regions, and this appears to be borne out by a study of fossil lists such as those contained in Bassler's *Bibliographic Index of Ordovician and Silurian Fossils* (1915). It is probable, however, that if instead of names actual specimens were brought into comparison, there would prove to be greater similarity between the faunas than appears at present.

Among the brachiopod genera which have been identified in British Ordovician or Silurian rocks, the following appear to be confined to the Ordovician: *Acrothele*, *Acrotreta?*, *Camarella*, *Christiania*, *Cliftonia*, *Clitambonites*, *Conotreta*, *Cyclospira?*, *Dinorthis*, *Orthis* (*Harknessella*), *Heterorthis*, *Hemipronites*, *Hyatella* (?), *Metacamerella*, *Micromitra*, *Monobolina*, *Orthis* (*Nicolella*), *Obolus*, *Orthorhynchula*, *Paterula*, *Porambonites*, *Protorhyncha*, *Protozyga*, *Pseudocrania*, *Rhinobolus?*, *Rhynchotrema*, *Schizambon*, *Schizocrania*, *Siphonotreta*, *Trematis*, *Zygospira*. The ? denotes that the generic determination is doubtful; within parentheses it means that it is doubtful whether the genus occurs in the Silurian.

Among the genera which make their first appearance in the Silurian are the following: *Anastrophia*, *Atrypina*, *Barrandella* (=*Clorinda*), *Brachyprion*, *Camarotoechia*, *Chonetes*, *Clintonella*, *Coelospira*, *Conchidium*, *Cyrtia*, *Dinobolus*, *Eichwaldia*, *Glassia*, *Gypidula*, *Stropheodonta* (*Leptostrophia*), *Meristella* (?), *Mimulus*, *Nucleospira*, *Pentamerus*, *Rhynchospira*, *Sieberella*, *Spirifer*, *Streptis*, *Stricklandinia*, *Uncinulus*, *Whitfieldella* (?), *Wilsonia*. The query mark in parentheses indicates that the genus has been doubtfully identified from the Ordovician, but is mainly Silurian. All except *Conchidium*, *Gypidula*, *Sieberella*, and *Wilsonia* occur in either the Upper or the Lower Llandovery, but a few are unknown in the Lower Llandovery. Among these may be mentioned *Atrypina*, *Chonetes*, *Cyrtia*, *Nucleospira*, *Spirifer*, *Uncinulus*.

Many other genera occur in both systems, though they are usually represented by different species. Among these are the following: *Atrypa*, *Bilobites*, *Catazyga* (?), *Crania*, *Dalmanella*, *Dayia*, *Discina*, *Hebertella*, *Hindella* (?), *Leptaena*, *Leptella*, *Lingula*, *Lingulasma?*, *Meristina*, *Orbiculoidea*, *Orthis*, *Parastrophia*, *Philhedra*, *Pholidops*, *Plaesiomys*, *Platystrophia*, *Plectambonites*, *Plectorthis*, *Rafinesquina*, *Rhipidomella*, *Rhynchotreta*, *Orthis* (*Schizophorella*), *Schuchertella*, *Stropheodonta*, *Strophomena*, *Strophonella*, *Triplecia*.

Certain species of these genera are recorded in published lists from Ordovician and Silurian rocks, ranging in age from the Bala to the Ludlow, but this is due in most cases to loose identifications. Thus, *Dalmanella elegantula*, so far as the writer is aware, does not occur below the Wenlock, and the specimens from the Bala and Llandovery which have been referred to that species can be readily distinguished from the Wenlock form. Similar remarks apply to such "long-ranging forms" as *Atrypa marginalis*, *Strophomena antiquata*, *Plectambonites sericeus* (which is confined to the Ordovician), and *P. transversalis* (which is confined to the Wenlock). Again, specimens of *Atrypa reticularis* from different horizons appear to be readily distinguishable from one another.

The British Ordovician rocks are distinguished by the extraordinary number of trilobite genera which they have yielded. The majority of these do not ascend into the Silurian, among which are

the following: *Agnostus*, *Amphilichas*, *Ampyx*,[1] *Apatocephalus*, *Asaphus*, *Bohemilla*, *Bronteopsis*, *Chasmops*, *Cheirurus* (*Cyrtometopus*), *C.* (*Nieszkowskia*), *C.* (*Sphaerocoryphe*), *Conolichas*, *Cybele*, *Cyclopyge*, *Dindymene*, *Dionide*, *Isotelus*, *Lichapyge ?*, *Menocephalus*, *Phillipsinella*, *Pliomera*, *Pterygometopus*, *Remopleurides*, *Salteria*, *Shumardia*, *Stygina*, *Telephus*, *Teratorhynchus*, *Triarthrus*, and *Trinucleus*.

Only three genera make their first appearance in the Silurian, viz.: *Cheirurus* (*Youngia*), *Deiphon*, and *Phacopidella*. The remaining genera occur in both systems and comprise the following: *Acidaspis*, *Arethusina*, *Bronteus*, *Calymene*, *Cheirurus*, *Cyphaspis*, *Encrinurus*, *Harpes*, *Homalonotus*, *Illaenus*, *Lichas* (*Corydocephalus*), *Metopolichas*, *Platylichas*, *Proetus*, *Sphaerexochus*, and *Staurocephalus*.

Very few species are, however, common to the two systems.

Since the rocks and fauna of the island of Anticosti[2] seem to present more resemblance to those of Britain than those of the American continent, they will best serve as a starting-point in the comparison of the British and American faunas.

The *English Head formation* yielded seventeen genera of brachiopods, all of which with the exception of *Pseudolingula* appear to occur in Britain. The four genera *Dinorthis*, *Rhynchotrema*, *Trematis*, and *Zygospira* are highly characteristic Ordovician types; most of the remainder are common to both systems. We note, however, the occurrence of *Dinobolus*, which does not occur below the Silurian, while the new genus *Protozeuga* is represented, according to Twenhofel[3] by the Wenlock species *Waldheimia Mawii Dav.* and *W.? glassii Dav.*

Nine trilobite genera are recorded, but as the American nomenclature differs somewhat from the British, exact comparison is not possible without reference to individual species. The genera *Amphilichas*, *Eoharpes*, *Isotelus* (with *Brachyaspis*), and *Pterygometopus*

[1] A single species of Ampyx has been recorded by Marr and Nicholson from the Valentian Stockdale shales.

[2] W. H. Twenhofel, *Bull. Victoria Memorial Mus.*, 3, 1914.

[3] *Op. cit.*, p. 30.

are, however, unknown in the British Silurian, while the species of *Encrinurus* (*E. multisegmentatus*) recorded is found only in the Upper Ordovician. The genus *Bumastus* is recorded only from Silurian rocks in Britain, but unless the name is used with different significance, it appears to occur commonly in the Ordovician in America. The remaining generic names, *Ceraurus* and *Ceraurinus*, seem to stand for forms which occur mainly in the British Ordovician. The brachiopod and trilobite fauna is, therefore, of distinctly Ordovician aspect, and if found in Britain, the formation in which it occurred would be unhesitatingly assigned to that system, and would probably be referred to the lower part of the Upper Bala.

The *Charleton formation* yielded twenty-six genera of brachiopods and eight genera of trilobites. Of the former, *Hyattidina* and *Pseudolingula* have not been found in Britain, while the three genera *Chonetes*, *Dinobolus*, and *Eichwaldia* first appear in the Silurian. The presence of *Clitambonites*, *Dinorthis*, *Rhynchotrema*, *Schizocrania*, *Trematis*, and *Zygospira* would be sufficient to assign this fauna to the Ordovician. Turning to the trilobites, the occurrence of *Chasmops* and *Isotelus* (and the allied genus *Brachyaspis*) lead to the same conclusion. The existence of *Chonetes* among such highly characteristic Ordovician forms is, therefore, unexpected and indicates a real difference between the British and American faunas.

In the *Ellis Bay formation*, out of twenty-four brachiopod genera five are Ordovician, two are of doubtful occurrence in Britain, fourteen are common to both systems, while three make their first appearance in the Silurian. These include *Chonetes* and *Dinobolus* from the lower beds, the third being *Atrypina*. The trilobites lead to the same conclusion as the brachiopods as to the strong Ordovician aspect of the fauna, *Chasmops*, *Isotelus*, and *Sphaerocoryphe* being associated with *Encrinurus multisegmentatus*. This fauna in Britain might be expected in the Upper Bala rocks and would certainly not be admitted into the Silurian.

Twenhofel records that the passage from the Ellis Bay to the *Becsie River formation* witnesses the extinction, mainly in the upper three zones, of about 80 per cent of the Ellis Bay fauna. Accordingly he regards the Becsie River formation as Silurian, a correlation which is in agreement with British usage.

Although only thirteen genera of brachiopods and four of trilobites occur, not one of these is confined to the Ordovician in Britain, while *Brachyprion*, *Camarotoechia*, *Clorinda* (=*Barrandella*), and *Coelospira* are distinctive of the Silurian.

In the *Gun River formation* and succeeding formations, the Silurian character of the fauna is thoroughly established, and there appear to be several species in common with British deposits. Most of these indicate a level above the Lower Llandovery of the type area and Haverfordwest. Among them we may note *Atrypa reticularis*, *Camarotoechia decemplicata*, *Coelospira hemispherica*, *Pentamerus oblongus*, and *Stricklandinia lirata*, while the type forms of *Clorinda linguifera* and *Plectambonites transversalis* are confined to the Wenlock. The rapidity with which many of the forms characteristic of the higher Llandovery and even of the Wenlock of Britain enter between the Ellis Bay and Gun River formations raises a doubt whether the Anticosti section is in reality as complete as it appears to be, since the Lower Llandovery formation, which is over 2,000 feet thick at Llandovery and Haverfordwest where it is best developed, must be represented in that island by only 188 feet of sediments. If, as their fauna suggests, the whole of the remaining Anticosti formations be assigned to the Upper Llandovery, the thickness of sediments of that age in the island is about one-half that of the British rocks. If the Becsie River formation truly represents the Lower Llandovery, as its position and to some extent its fauna seem to demand, its thickness is much less than would be expected if the record of sedimentation is approximately complete.

Twenhofel tentatively correlates both the Becsie River and Gun River formations with the Lower Llandovery, but this is based on erroneous records in British literature of *Pentamerus oblongus*, *Clorinda linguifera*, and *Coelospira hemispherica* in the Lower Llandovery. *Stricklandinia lens*, with which *S. davidsoni* of Anticosti has been compared, runs through the greater part of the Llandovery, but there is some evidence in Britain of mutations which have a more restricted range. The author is now engaged upon a revision of the British pentamerids.

When we turn from Anticosti, where the boundary between Ordovician and Silurian has been drawn at the same level as it

would be by British geologists, to the rest of the American continent, we meet with a distinct difference of opinion as to the position in the vertical succession to be assigned to that level. In the Correlation Table attached to Bassler's *Bibliographic Index of American Ordovician and Silurian Fossils*, the Ordovician includes the four divisions Big Buffalo, Chazyan, Mohawkian, and Cincinnatian, the latter including in turn the Eden and Maysville formations. The Silurian apparently follows the latter (Pl. I, II) and is divided (Pl. III, IV) into the three divisions Medinan, Niagaran, and Cayugan. The Medinan includes the Richmond and the Albion; the Niagaran includes the Clinton and Lockport. If the base of the Silurian is drawn at the base of the Medinan and the Richmond is accordingly assigned to the Silurian,[1] then the boundary is clearly drawn at a very different level from that in Anticosti and in Britain. Twenhofel regards the English Head and Charleton formations as almost exact equivalents of the Richmond, but he concludes that the Ellis Bay formation, which he tentatively assigns in part at least to the Upper Bala of Britain, has no equivalent on the North American continent. The Ordovician character of the Richmond appears by a direct comparison of the brachiopods and trilobites listed from this formation from the interior states in the *Bibliographic Index* (pp. 1476–83). Thus, in the area adjacent to the Cincinnati axis the genera *Dinorthis*, *Rhynchotrema*, *Trematis*, and *Zygospira* and the trilobite genus *Isotelus* are Ordovician types, while there is no genus which is distinctively Silurian. In the Richmond of the upper Mississippi Valley we find recorded, in addition to the above, such thoroughly Ordovician trilobites as *Megalaspis*, *Nileus*, *Pterygometopus*, and *Sphaerocoryphe*. No one in Britain would refer to the Silurian any rocks that yielded such a fauna. Moreover, Ulrich[2] records *Dicellograptidae* in the Richmondian Maquoketa shale of the Mississippi Valley. This in itself would be sufficient in Britain to identify the formation as Ordovician. Evidently, however, the graptolites have not the same importance in America as in Britain, for when a British geologist comes across the phrase "early Silurian species of *Dicellograptidae*," he experiences a distinct shock.

[1] *Bibliographic Index*, p. 1476.

[2] *Op. cit.*, p. 25.

It is more difficult to define the position of the faunas accredited to the *Upper Medinan* division. The fossil lists suggest that these deposits from different localities may belong to somewhat different horizons. The Upper Medinan (Girardeau) of Missouri and Illinois contains only one doubtfully identified Ordovician brachiopod genus; on the other hand, its somewhat limited fauna contains no distinctive Silurian forms; it is, therefore, impossible to decide its affinities by reference to British fossil occurrences alone. The Edgewood of the same region contains *Camarotoechia*, *Clorinda?*, *Pentamerus*, and *Brachyprion*, suggesting Silurian affinities, but *Isotelus* also occurs. One would be tempted to regard a fauna into which pentamerids entered as Silurian. In the Upper Medinan (Brassfield) of Ohio, Kentucky, etc., not only are distinctive Ordovician types absent, but the fauna has a strong Silurian aspect from the presence of *Camarotoechia*, *Rhynchotreta*, *Stricklandinia*, and *Deiphon;* further, some of the species recorded are well-known Silurian types, e.g., *Deiphon forbesi*, *Dalmanella elegantula*, *Plectambonites transversalis*, and *Rhipidomella hybrida*. All these forms would be regarded in Britain as indicative of Upper Llandovery if not of Wenlock rocks.

The same remarks apply to the Upper Medinan (Cataract) of Ontario, with *Camarotoechia*, *Coelospira*, *Dalmanella elegantula*, *Plectambonites transversalis*, *Rhipidomella hybrida*, and *Uncinulus stricklandi*.

All *Clinton* faunas, whether Lower or Upper, must, if fossils have any value, be later than the Lower Llandovery. Such forms from the Lower Clinton of New York and Appalachian Valley as *Atrypa reticularis*, *Atrypina*, *Coelospira hemispherica*, *Conchidium*, *Cyrtia*, *Dalmanella elegantula*, *Monograptus clintonensis*, *M. priodon*, *Nucleospira*, *Pentamerus oblongus*, *Plectambonites transversalis*, *Retiolites genitzianus*, *Camarotoechia decemplicata*, *Stricklandinia canadensis* (=*S. lirata*), and *Spirifer radiatus* would be quite out of place in the Lower Llandovery, but several of these forms make their appearance in Britain at the base of the Upper and persist through the formation into the Wenlock.

It appears, then, that while both Upper Bala and Upper Llandovery rocks can be recognized in North America in the Richmond and Clinton formations respectively, it is doubtful whether the Low-

er Llandovery is represented at all, and in Britain this formation as regards thickness of sediments is equally important with Upper Llandovery or Wenlock. The same doubt was expressed above in regard to Anticosti. Of the Albion, which is tentatively correlated with that formation: a part of it—the Brassfield—is almost certainly Upper Llandovery, the other parts being of doubtful affinities, and one only, the Edgewood, suggests an overlap of Ordovician and Silurian faunas.

In spite of certain difficulties which the correlation of the formations in such widely distant regions presents, it is satisfactory to find that it is possible to arrive at certain definite conclusions by the use of genera alone. If the herculean task were undertaken of making a detailed comparison of the succession of specific types in the two countries, it is probable that more detailed correlations could be achieved. There is no doubt that the faunas are more alike than fossil lists would suggest, and it is to be hoped that the time is not far distant when more ample facilities will be available to enable students of Paleozoic geology to compare directly the fossil faunas on the two sides of the North Atlantic basin.

# THE GRENVILLE PRE-CAMBRIAN SUBPROVINCE[1]

M. E. WILSON

ABSTRACT

This paper is chiefly (1) an outline of the geology of the territory lying along the southern border of the Canadian pre-Cambrian shield in southeastern Ontario and the adjacent parts of Quebec, and (2) a comparison of the formations of this region with those of the territory extending from Lake Huron and Lake Superior to Lake Timiskaming and Lake Mistassini—the Timiskaming subprovince. The bed-rock formations of the Grenville subprovince, except for a few late pre-Cambrian igneous intrusives, all belong to a basal complex composed of three rock groups: (1) a group of marine sediments with some locally associated volcanics—the Grenville and Hastings series; (2) a related series of igneous intrusives—peridotite, gabbro, diorite, shonkonite, etc.; and (3) batholithic masses of syoenite and granite. A comparison of these formations with those composing the basal complex of the Timiskaming subprovince shows that with the exception of group 3, the formations of the two regions are almost entirely different and for this reason cannot be definitely correlated.

By far the greater part of our information regarding the geology of the Canadian pre-Cambrian shield has been obtained in the territory lying along its southern border and chiefly in four districts or subprovinces: (1) the region northwest of Lake Superior, (2) the region south of Lake Superior in the United States, (3) the region extending northeast from Lake Superior and Lake Huron to Lake Timiskaming and Lake Mistassini—the Timiskaming subprovince—(4) southeastern Ontario, the southern Laurentian highlands of Quebec, and the Adirondack region, which together form the Grenville subprovince. These districts are geographically and geologically separate from one another, for between the Grenville and the Timiskaming subprovinces there intervenes a belt of banded gneisses; between the Timiskaming subprovince and the western subprovinces there are the wooded pre-Cambrian high lands largely underlain by granite and granite gneiss on the north and the overlapping Paleozoic sediments on the south; and between the northwestern and southwestern subprovinces lies Lake Superior.[2]

[1] Published with the permission of the director of the Geological Survey of Canada. Paper presented at the meeting of the British Association for the Advancement of Science, Toronto, August, 1924.

[2] M. E. Wilson, "The Subprovincial Limitations of Pre-Cambrian Nomenclature in the St. Lawrence Basin," *Journal of Geology*, Vol. XXVI (1918), pp. 325–33.

The purpose of this paper is (1) to outline briefly the geology of the most easterly of these subdivisions, the Grenville subprovince, and (2) to indicate the most probable relationships of the formations of the Grenville subprovince to those of other parts of the Canadian shield and more particularly to those of the Timiskaming region, to which, because of their proximity, they are probably most closely related.

## GEOLOGY OF THE GRENVILLE SUBPROVINCE

### SOUTHEASTERN ONTARIO AND THE SOUTHERN LAURENTIANS OF QUEBEC

The Canadian part of the Grenville subprovince, that is, the territory in southeastern Ontario and the northern part of the lower St. Lawrence valley underlain by pre-Cambrian rocks, is the region in which Logan, Murray, Ells, and others of the earlier geologists on the staff of the Geological Survey of Canada carried on a large part of their work. It is also the region in which the name Laurentian was proposed and defined by Logan. The most notable investigations of later years in the belt have been the study of the anorthosite region northwest of Montreal by Adams,[1] the examination of the Bancroft sheet in southeastern Ontario by Adams and Barlow,[2] and the study of the areas of Hastings conglomerate occurring in the Madoc district, Ontario, by Miller and Knight.[3] The only other reports on the belt, outside of those by the writer, are those by M. B. Baker on the Kingston district[4] and the *Memoir* on the Brockville-Mallorytown area by J. F. Wright.[5]

The writer's information regarding the geology of the belt is based on field work carried on continuously for the past twelve years in nine different map areas selected here and there, but chiefly

[1] "Report on the Geology of a Portion of the Laurentian Area Lying to the North of the Island of Montreal," *Geological Survey of Canada, Annual Report*, Vol. VIII (1895), Part J.

[2] "Geology of the Haliburton and Bancroft Areas," *Geological Survey of Canada, Memoir No. 6*, 1910.

[3] "The Pre-Cambrian Geology of Southeastern Ontario," *Bureau of Mines, Ontario, Annual Report*, Vol. XXII (1914), Part 2.

[4] *Ibid.*, Vol. XXVI (1917), Part 3, and Vol. XXXI (1923), Part 6.

[5] *Geological Survey of Canada, Memoir 134*, 1923.

in succession from east to west and hence nearly at right angles to the structural trend of the underlying bed rocks (Fig. 1).

The formations of the Grenville subprovince in Ontario and Quebec, except for the unconsolidated Pleistocene and Recent deposits and a few intrusions of lamprophyre, diabase, granite, and

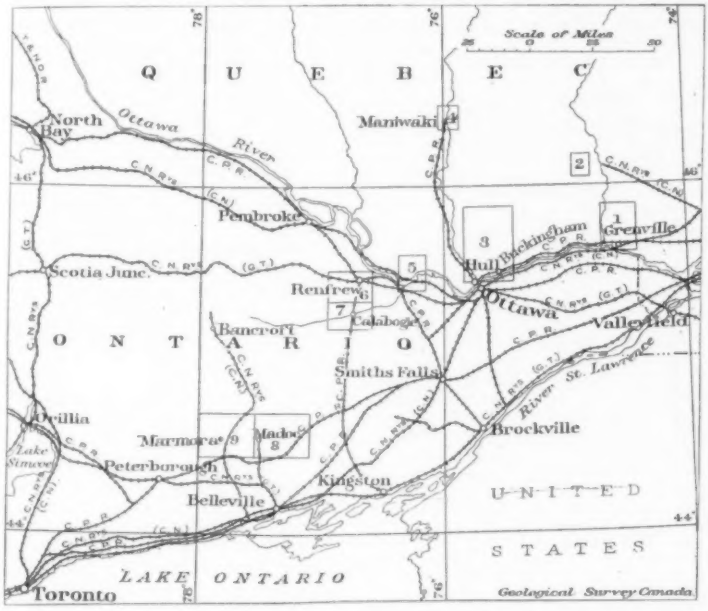



FIG. 1.—Index map showing areas in the Grenville subprovince examined. Map areas: (1) Grenville; (2) St.-Rémi-d'Amherst; (3) Buckingham; (4) Maniwaki; (5) Arnprior-Quyon; (6) Renfrew; (7) Calabogie; (8) Madoc; (9) Marmora.

syenite, of late pre-Cambrian age, all belong to a typical basal complex. This constitutes the Laurentian of Logan, and because of its highly metamorphosed condition has always been regarded as early pre-Cambrian in age. The formations are in some respects the same throughout the whole region, but certain differences exist between its western and eastern parts, as shown in the tabular statement (Table I) of the succession of formations in each.

TABLE I

FORMATIONS IN GRENVILLE PRE-CAMBRIAN SUBPROVINCE

| | | Western Part | | Eastern Part | |
|---|---|---|---|---|---|
| Late pre-Cambrian (Huronian of Logan) | | Diabase dykes | | Grenville and Rigaud stocks of granite and syenite | |
| | | | | Diabase dykes | |
| | | | | Lamprophyre mass and dykes | |
| Early pre-Cambrian (Laurentian of Logan) | | Batholithic intrusives | Granite, granite gneiss, and pegmatite | Batholithic intrusives | Granite, granite gneiss, and pegmatite |
| | | | Syenite and syenite gneiss | | Syenite and syenite gneiss |
| | | Gabbro and diorite | | | |
| | | Hastings series | Limestone, dolomite, argillite, greywacke, and conglomerate | Buckingham series (igneous) | Pegmatite, shonkinite, pyroxene diorite, norite, anorthosite, peridotite, etc. |
| | | Gabbro and diorite ? | | | |
| | | Grenville series | Crystalline limestone, dolomite, quartzite, mica schist, sillimanite-garnet gneiss, and lava flows | Grenville series | Crystalline limestone, sillimanite-garnet gneiss, and quartzite |

GRENVILLE AND HASTINGS SERIES

*Eastern part.*—The oldest rocks in the eastern part of the Grenville belt belong to what has been known as the Grenville series, so named after the township of Grenville, where they were first studied by Logan. It is believed that the rocks of this series were originally laid down as alternating beds of shale, sandstone, and limestone, but owing to the intense metamorphism to which they have been subjected, the shale has been recrystallized to sillimanite-garnet gneiss, the sandstone to vitreous quartzite, and the limestone to crystalline limestone. The reasons for this conclusion are: (1) Chemical analyses of the sillimanite-garnet gneiss member of the series show that in every detail this rock has the composition of a shale,[1] and thus the three rock types, sillimanite-garnet gneiss, quartzite, and crystalline limestone, have respectively the composi-

[1] F. D. Adams, *Geological Survey of Canada, Annual Report*, Vol. VIII (1895), Part J, pp. 57–61.

tion of the three dominant members of marine sedimentary series of the well-sorted types; and (2) these rocks occur interstratified with one another in a manner similar in every respect to the way normal marine sedimentary deposits usually occur.

The analyses of seven samples of the sillimanite-garnet gneiss, three of which were collected by Adams, one by Osann, and three by the writer, are included in Table II. The noteworthy feature

TABLE II

CHEMICAL ANALYSES OF SILLIMANITE-GARNET GNEISS

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 61.96 | 57.66 | 74.70 | 58.68 | 60.33 | 49.61 | 55.18 | 60.15 |
| $Al_2O_3$ | 19.73 | 22.83 | 8.88 | 16.17 | 17.17 | 22.00 | 20.70 | 16.45 |
| $Fe_2O_3$ | ..... | ..... | 9.64 | 1.66 | 3.93 | 1.93 | 4.50 | 4.04 |
| FeO | 4.60 | 7.74 | ..... | 5.69 | 6.55 | 9.55 | 5.65 | 2.90 |
| $FeS_2$ | 4.33 | ..... | ..... | ..... | ..... | ..... | ..... | ..... |
| MgO | 1.81 | 3.56 | 1.87 | 3.71 | 3.35 | 6.33 | 3.49 | 2.32 |
| CaO | 0.35 | 1.16 | 1.07 | 0.30 | 0.90 | 0.36 | 0.34 | 1.41 |
| $Na_2O$ | 0.79 | 0.60 | 0.42 | 0.83 | 0.73 | 1.40 | 1.81 | 1.01 |
| $K_2O$ | 2.50 | 5.72 | 0.95 | 8.68 | 4.57 | 3.88 | 4.75 | 3.60 |
| $H_2O+$ | 1.82 | 1.50 | 1.05 | 1.65 | 1.00 | 2.20 | 1.80 | 3.82 |
| $H_2O-$ | | | | | ..... | ..... | ..... | 0.89 |
| $CO_2$ | ..... | ..... | ..... | 0.36 | ..... | ..... | ..... | 1.46 |
| $TiO_2$ | 1.66 | ..... | ..... | 1.39 | 1.52 | 2.00 | 1.72 | 0.76 |
| $SO_3$ | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 0.58 |
| $P_2O$ | ..... | ..... | ..... | 0.31 | 0.04 | 0.06 | 0.10 | 0.15 |
| BaO | ..... | ..... | ..... | ..... | ..... | ..... | ..... | .04 |
| MnO | trace | trace | 0.50 | ..... | 0.09 | 0.05 | 0.05 | trace |
| C | ..... | ..... | ..... | ..... | ..... | ..... | ..... | 0.88 |
| | 99.55 | 100.77 | 99.08 | 99.43 | 100.18 | 99.37 | 100.09 | 100.46 |
| Specific Gravity | ..... | ..... | ..... | ..... | 2.976 | 3.006 | 2.930 | ..... |

1. Quebec, Joliette County, about 1 mile west of the Church of St.-Jean-de-Matha, Seigniory of De Ramsay, *Geological Survey of Canada, Annual Report*, Vol. VIII (1895), Part J, p. 58.

2. Quebec, Papineau County, west shore Trembling Lake, *ibid.*

3. Quebec, Montcalm County, Rawdon township, Darwin Falls, near village of Rawdon, *ibid.*

4. Ontario, Prescott County, south shore of Ottawa River, opposite Montebello, Quebec, *ibid.*, Vol. XII (1899), Part O, p. 5.

5. Quebec, Papineau County, Portland East township, RangeI, Lot 12. Analysis by M. F. Connor.

6. Quebec, Papineau County, Buckingham township, Range XII, Lot 19. Analysis by M. F. Connor.

7. Quebec, Papineau County, Buckingham township, Range XII, Lot 19. Analysis by M. F. Connor.

8. A composite analysis of 51 Paleozoic shales by H. N. Stokes, F. W. Clarke, "Data of Geochemistry," *United States Geological Survey, Bulletin 616*, 1916, p. 546.

about these analyses is that when compared with the composite analysis of 51 Paleozoic shales, in column 8, it is seen that they, for the most part, contain a much lower percentage of the most soluble constituents—soda and lime—and a much higher content of the least soluble constituents—alumina, magnesia, and potash. It would seem, therefore, that the processes of rock decomposition and the sorting of the products of this decomposition were carried to at least the same degree of completion in the early pre-Cambrian as during later geological epochs.

*Western part.*—The oldest formations occurring in the western part of the Grenville belt consist chiefly of limestone and other sediments of the well-sorted type similar to those in the eastern part, but they belong to two series separated by an unconformity. The older of these has been classed as Grenville, whereas the younger has been called the Hastings series after the county of Hastings, in which it is most extensively developed.

The Grenville series in the western part of the belt is distinguished from that in the eastern part by the presence of interstratified lava flows, by its less metamorphosed condition, and by the large proportion of mica schist and the relatively small proportion of sillimanite-garnet gneiss which it includes. The Hastings series consists chiefly of gray, blue-weathering limestone interstratified with argillite, except near its base, where beds of conglomerate, interstratified with argillite, buff-weathering dolomite, greywacke, and mica schist occur. It contains well-rounded pebbles and bowlders of both the igneous and sedimentary members of the Grenville series and, therefore, overlies it unconformably. Both series appear to be folded to about the same degree, however, and where the Hastings series overlies the sedimentary members of the Grenville series there is no noticeable discordance in dip. It seems probable, therefore, that no important structural disturbance occurred during the period of erosion that intervened between the deposition of the two series.

In the Madoc district the rocks of the basal pre-Cambrian complex are less metamorphosed than in any other part of the Grenville subprovince. Furthermore, the members of the Hastings series, except for the conglomerate, are lithologically similar to those of the

Grenville series and where metamorphosed cannot be distinguished from them. It is probable, however, that metamorphism has not been so intense in most parts of the Grenville subprovince but that conglomerate similar to that in the Madoc district could be recognized if present. The fact that the Hastings conglomerate has not been found in other parts of the Grenville subprovince indicates, therefore, that the Hastings series is confined to southeastern Ontario and is either a local phase of the Grenville series, as suggested by Adams and Barlow[1] or a series of local extent younger than the Grenville series. In either case, the separation of the Hastings series from the Grenville series, except in the typical locality, is going to be a very tedious if not an almost impossible task.[2]

In this connection it is interesting to note that the lava flows interstratified with the sediments of the Grenville series in the western part of the Grenville subprovince occur abundantly beneath their contact with the overlying Hastings series, the Hastings conglomerate and greywacke resting directly on the volcanics in many places. It would seem evident, therefore, that the volcanics belong to the upper part of the Grenville series.

### BUCKINGHAM SERIES

The Buckingham series is a group of igneous pyroxenic rocks found widely distributed throughout the pre-Cambrian basal complex of the southern Laurentian highlands of Quebec. Its members range in composition from peridotite to granite pegmatite, but gabbro, anorthosite, pyroxene diorite, and pyroxene syenite (shonkinite) are its most abundant representatives. They have been intruded into the Grenville series partly as dykes or as sills injected between the beds or along the planes of foliation, and partly as large lenticular masses (possibly deformed laccoliths) or in some cases in masses of batholithic dimensions. They have all a granular texture, generally contain a pink to pale-green monoclinic pyroxene as their most abundant ferromagnesian constituent, and are younger in age than the Grenville series and older than the batholithic intru-

[1] *Op. cit.*, p. 402.

[2] It is not possible to discuss the relationships of the Hastings and Grenville series fully in a brief summary description of the geology of the Grenville subprovince. It is the writer's intention to present the results of field work on this problem in a later paper.

sions of granite and syenite gneiss. In consideration of the wide extent of these rocks, their peculiar mineralogical composition, their evident genetic relationship to one another, and their approximate contemporaneity, they have been grouped together as the Buckingham series.

### GABBRO AND DIORITE

In the western part of the Grenville subprovince there are numerous dykes, sills, and masses of gabbro and diorite that are intrusive into the Grenville or Hastings series and are in turn themselves intruded by the batholithic masses of granite and syenite gneiss. They, therefore, occupy about the same position in the geological succession as the Buckingham series, except that the gabbro and diorite that intrudes the Grenville series is not necessarily of the same age as that intruding the Hastings, for the extrusions of lava that occurred during the Grenville epoch would almost certainly be accompanied by intrusions of similar rocks, so that, as suggested in the table of formations, gabbro and diorite older than the Hastings series are almost certainly present. It might be possible also that the volcanics of the Grenville series are the superficial equivalent of the Buckingham intrusives.

### BATHOLITHIC INTRUSIVES

Throughout the whole of the Grenville belt in southeastern Ontario and Quebec, the Grenville series, the Hastings series, the Buckingham series, and the gabbro and diorite are intruded by dykes, sills, and batholiths of (1) biotite-hornblende syenite and syenite gneiss and (2) biotite or biotite-hornblende granite and granite gneiss. The first of these are generally coarse-grained prophyritic rocks, and the second fine-grained aplite-like types passing in places into extensive areas of fine pegmatite. Wherever the two groups occur together, the granite is seen to intrude the syenite phase. Since no other rocks have been found to intervene between the two groups, there is no evidence to indicate whether they belong to separate or one period of batholithic invasion. It may be possible that they are widely separated in age, but the younger rock is much more acidic than the older, and it is in this way that differentiation would probably occur where a magmatic invasion is broken into

successive intrusions. It is also possible, therefore, that they are merely phases of a single invasion.

Where the batholithic rocks occur in large masses or in sills, they are, as a rule, foliated. The small masses and dykes, especially where they have been intruded into limestone, are usually massive. For this reason the massive phase has been regarded as younger in age than the foliated phase. This may be possible, in some cases at least, but it is also evident that if the foliation developed in the intrusives during their consolidation, a small mass would cool more quickly and would therefore afford less opportunity for foliation to develop. Furthermore, where the intrusive mass is inclosed in limestone which is very incompetent under deep-seated conditions the limestone may take up the deformation and the intrusive remain massive.

An interesting feature exhibited by the sills and batholiths of granite gneiss is that the strike and dip of the foliation is almost invariably parallel to that of the adjacent Grenville sediments, and in places sills or phacoliths of the intrusive can be observed to increase noticeably in width on the crests of folds. In the scattered areas studied by the writer, the granite intrusives conform almost everywhere to the structure of the inclosing sediments. A typical example of this is shown in Figure 2. This would seem to indicate almost conclusively that the magma underwent deformation during its consolidation. It was probably this relationship that, in part at least, led Logan and the other early geologists of the Canadian Geological Survey to regard these igneous gneisses as sediments.

### LATE PRE-CAMBRIAN INTRUSIVES

The only pre-Cambrian rocks in the Grenville belt that are not metamorphosed are scattered igneous intrusions of three classes: (1) lamprophyre, (2) diabase, and (3) granite and syenite. The lamprophyre is confined, so far as known, to a few dykes and a single mass, about 1 square mile in area, of riebeckite kersantite, situated east and south of the town of Buckingham, Quebec. The diabase occurs here and there throughout the belt in dykes from a few inches to several hundred feet in width, and is especially well developed in an east-west trending zone over 100 miles in length lying along the

southern border of the Laurentian highlands to the north of the Ottawa River between the Ottawa district and the region north of Montreal. In this zone they form a remarkably parallel system, a

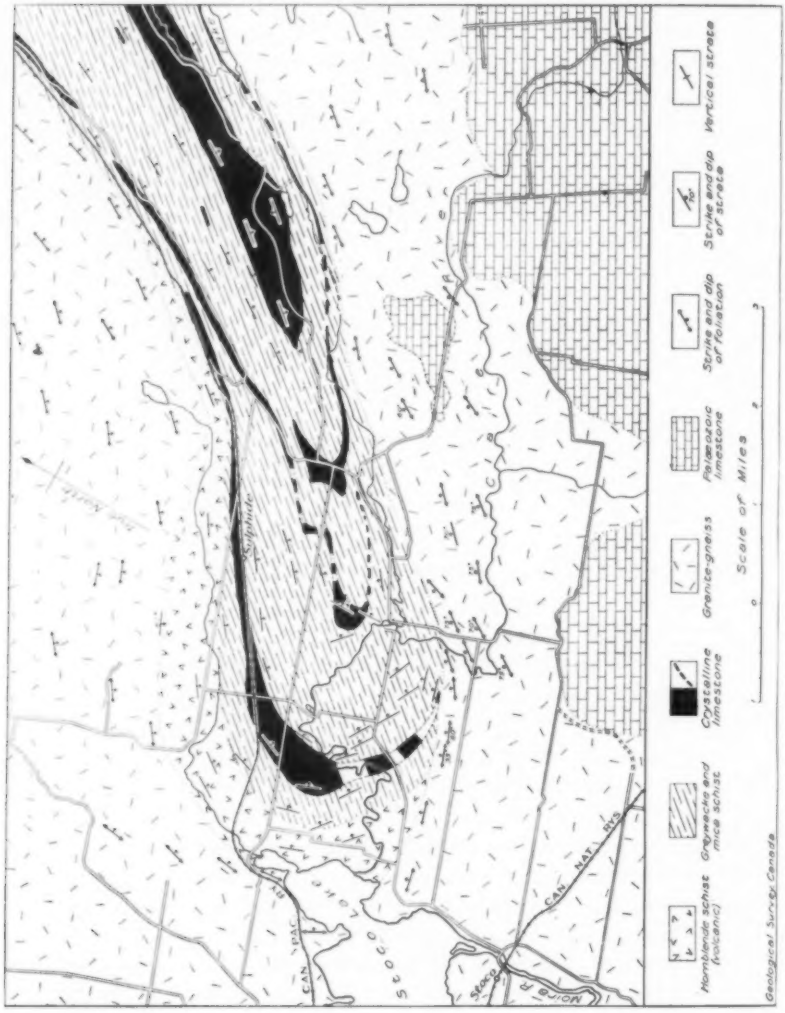



FIG. 2.—Diagram showing the relationship of granite gneiss to the Grenville-Hastings volcanics and sediments of the Claire River syncline, Hungerford Township, Hastings County, Ontario.

feature well shown in the map of the Buckingham district (Fig. 3). The kersantite mass at Buckingham is cut by one of these dykes, so that the diabase is younger than the lamprophyre. The granite and syenite forms the Grenville and Rigaud stocks, two rock knobs about 4 miles in diameter situated on opposite sides of the Ottawa River a few miles northwest of Montreal. These do not intrude the overlying Upper Cambrian (Potsdam) sandstone, but the Grenville mass cuts off a diabase dyke. They are, therefore, younger than the diabase and pre-Cambrian or at least pre-Potsdam in age.

### ADIRONDACK REGION

The pre-Cambrian formations composing the Adirondack Mountains of New York State, as described by Kemp, Smyth, Cushing, and W. J. Miller,[1] are remarkably similar to those in the eastern part of the Grenville geosyncline in Canada. In the pre-Cambrian basal complex of this region, as in Quebec, there are three main groups of rock: (1) the Grenville series, (2) anorthosite and gabbros similar to these members of the Buckingham series, and (3) batholithic intrusions of granite and syenite; but Cushing maintained that there is also a granite gneiss present that is older than the anorthosite and gabbro.[2] This conclusion is disputed by Miller,[3] however, and has also been questioned by J. F. Wright.[4]

In those districts in Canada studied by the writer, the anorthosite, gabbro, and other members of the Buckingham series were not observed to intrude or to contain inclusions of granite or syenite gneiss, but, on the other hand, where massive they are intruded by dykes, and where foliated they are injected by sills or phacoliths of granite. Within the limitations of these areas, therefore, the writer's observations support Miller's contention.

The late pre-Cambrian, that is, the unmetamorphosed pre-Cambrian rocks of the Adirondack region consist entirely of igneous intrusives among which diabase dykes similar to those in Canada are represented.

[1] *Journal of Geology*, Vol. XV (1907), pp. 206–8; *New York State Museum, Bulletin 193*, 1917.

[2] *American Journal of Science*, Vol. XXXIX (1915), pp. 288–94.

[3] *Bulletin of the Geological Society of America*, Vol. XXV (1914), pp. 243–63.

[4] *Op. cit.*, pp. 31–32.

FIG. 2.—Diagram showing the relationship of granite gneiss to the Grenville-Hastings volcanics and sediments of the Claire River syncline, Hungerford Township, Hastings County, Ontario.

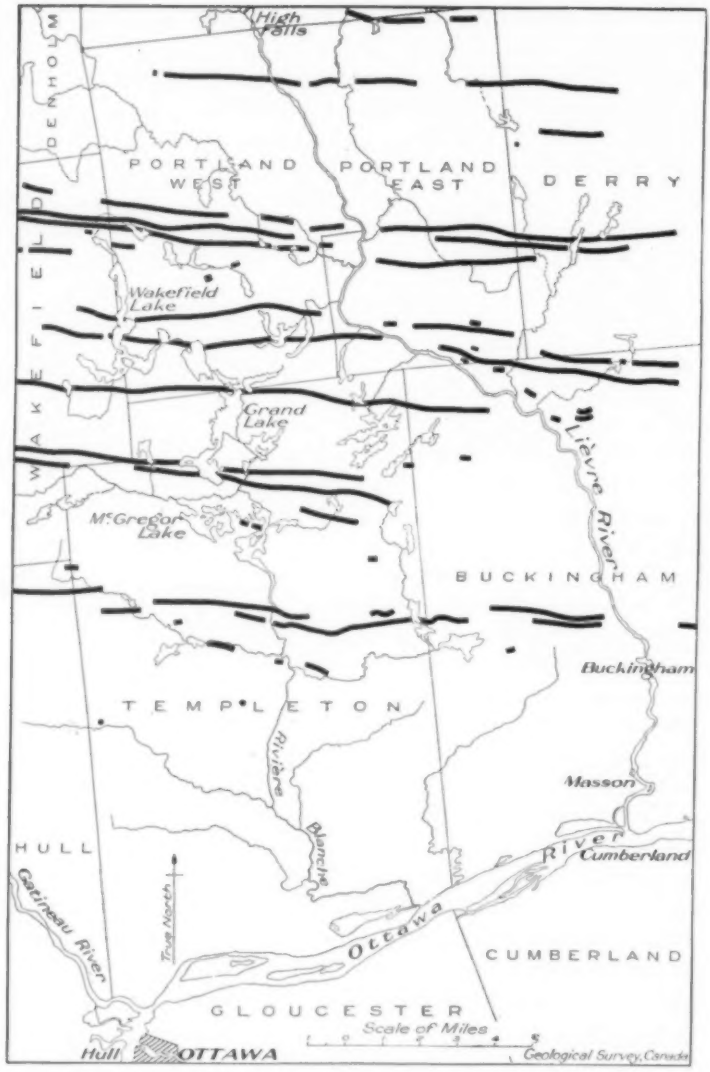



FIG. 3.—Diagram showing the system of parallel late pre-Cambrian diabase dykes that crosses the Buckingham map area, Quebec.

### RELATIONSHIPS OF THE FORMATIONS OF THE GRENVILLE AND TIMISKAMING SUBPROVINCES

On proceeding northward in the Grenville subprovince, the areas of Grenville series, Buckingham series, and gabbro-diorite become less and less extensive and are finally replaced by a northeasterly trending belt of banded granite, syenite, and other gneisses, from 25 to 40 miles wide. North of this belt of banded gneisses volcanic flows and clastic sediments forming the Timiskaming belt occur. These relationships suggest that the belt of banded gneisses is the truncated batholithic base of an ancient mountain chain intervening between geosynclines of surface rocks—volcanic flows and sediments—that underlie the Timiskaming and Grenville subprovinces.[1]

The correlation of the formations of the Grenville and Timiskaming geosynclines is difficult, not only because the two belts are separated from one another by the belt of banded gneisses, but because the formations in each are almost entirely different. In both belts there is a basal complex the youngest member of which is granite and syenite, but the surface rocks of the complex in the Timiskaming subprovince are largely volcanic flows with some associated poorly sorted clastic sediments, whereas the surface rocks of the Grenville subprovince are dominantly limestone and other well-sorted clastic sediments suggesting a marine origin, with lava flows in subordinate amounts. Another great difference between the two belts is the presence of a great thickness of relatively undisturbed late pre-Cambrian, Huronian sediments intervening between the basal complex and the Paleozoic in the Timiskaming belt, and the apparent absence of these in the Grenville belt. There are, therefore, few data upon which positive correlations of the formations in the two belts can be based, and in attempting their correlation several hypotheses must be considered. Of these the most important are the following (1) that the Grenville series is entirely, or in part, equivalent in age to the Huronian, a possibility suggested to the writer several years ago by W. H. Collins and recently advocated

[1] M. E. Wilson, *American Journal of Science*, Vol. XXXVI (1913), pp. 109–22; *Geological Survey of Canada, Memoir 103*, 1918, p. 46.

by Quirke;[1] (2) that the youngest members of the basal complex in each subprovince, the batholithic intrusions of granite, granite gneiss, and related rocks, are of the same or about the same age; (3) that the surface rocks of the basal complex in the Grenville subprovince are (*a*) younger, (*b*) correlative with, (*c*) older than the surface rocks of the basal complex in the Timiskaming belt; and (4) that the unconformity that separates the Hastings from the Grenville series is the same as that between the Timiskaming sediments and the underlying Abitibi (Keewatin) volcanics.

1) Several years ago it was discovered by Collins at Killarney[2] on the north shore of Lake Huron that a batholith of granite, which he regards as not only post-Huronian but post-Keweenawan in age, occurs on the northwestern margin of the belt of banded gneisses. On its eastern margin this batholith appears to merge into the banded gneisses, and for this and other reasons Collins and more recently Quirke have suggested that the Grenville series may be Huronian. There are, however, objections to this conclusion. It implies that the Buckingham series and the gabbro and diorite that intrude the Grenville and Hastings series are post-Huronian (probably Keweenawan) in age, although except for dykes and sills of diabase, and norite in the Sudbury district, there are no corresponding post-Huronian rocks present in the Timiskaming belt. It assumes that the batholiths of granite and syenite that occur throughout the Grenville belt are post-Keweenawan in age and that the whole of southeastern Ontario and the Adirondack region was mountain built and peneplained in the interval between the Keweenawan epoch and the beginning of Paleozoic time. Throughout the Grenville subprovince, as throughout a large part of the Canadian shield, the pre-Cambrian basal complex is cut by dykes of diabase which are lithologically similar to the diabase of Keweenawan age in the Lake Superior district and which have been generally regarded as Keweenawan. In the Ottawa Valley, as previously explained, two pre-Cambrian stocks of granite and syenite occur, one of which cuts off a dyke of the diabase. It would seem more reasonable to assume

[1] *Bulletin of the Geological Society of America*, Vol. XXXV (1924), pp. 89–90.

[2] "The Age of the Killarney Granite," *Geological Survey of Canada, Museum Bulletin No. 22*, 1916.

that these stocks are of Killarney age, and in that case the Grenville series would not be Huronian. On the shores of Lake Timiskaming the banded gneisses are overlain unconformably by the (Huronian) Cobalt series.[1] It is evident, therefore, that if the Killarney batholith intrudes the Cobalt series at Killarney, it terminates in the interval between Killarney and Lake Timiskaming, and if it terminates in a northeasterly direction, may it not also terminate toward the southeast?

2) If the Killarney granite belongs to a younger batholith intrusive into the banded gneisses, then it is probable that the basal complex of the Grenville region is pre-Huronian in age and that the youngest members of the basal complex in both subprovinces, the batholithic granite and syenite, were intruded about the same time, as has been generally assumed. The reasons that this seems probable are that the batholiths of granite and syenite in the Timiskaming belt and the banded gneisses that separate the Timiskaming from the Grenville belt (omitting gneisses of Killarney age from consideration) have the same geological relationships, that is, they are all intrusive into the other rocks of the basal complex and are separated by a paleoplain from the overlying Huronian. In the Grenville belt the batholiths of granite and syenite and the belt of banded gneisses are likewise younger than all the other rocks of the complex. Hence their relationships are apparently the same. There is of course the possibility, despite this similarity in relationships, that the batholiths of the Grenville belt were intruded at a different time from those of the Timiskaming region, or that the batholiths of each subprovince are not all of the same age. The first of these possibilities is suggested by the difficulty with which the Killarney batholith is being delimited. If this batholith had not been associated with pre-Cambrian late pre-Cambrian (Huronian) sediments, its relationship to the surface rocks of the basal complex would have been the same as that of the banded gneisses, and its widely separate age could not have been established. The second possibility is indicated in the Timiskaming region by the presence of pebbles of granite in

[1] A. E. Barlow, *Geological Survey of Canada, Annual Report*, Vol. X, Part I (1897), p. 188. M. E. Wilson, "An Area Adjoining the East Side of Lake Timiskaming," *Geological Survey of Canada*, 1911, p. 17.

some of the belts of sediments (Timiskaming, Sudbury, Pontiac series, etc.), although the source[1] of these pebbles has not yet been discovered; and in the Grenville belt by the presence of syenite intruded by granite in many of the batholithic massifs as previously[2] described. All that can be concluded, therefore, regarding the batholithic intrusives of these regions is that, if it be established that the Killarney granite is of local extent and intrusive into the banded gneisses, then it is probable that the development of the pre-Huronian paleoplain was preceded by batholithic invasion or invasions that extended throughout the whole of the Timiskaming and Grenville subprovinces.

3) The pre-batholithic surface rocks—sediments and volcanic flows—of the Timiskaming and Grenville geosynclines may obviously have any one of three relationships to one another. The Grenville-Hastings complex may be (*a*) younger than, (*b*) correlative with, or (*c*) older than the Abitibi (Keewatin)—Timiskaming complex. In favor of the first of these it may be pointed out that since pre-Cambrian time the Canadian shield has been almost continuously a land area, that it is probable that this positive tendency was characteristic of the shield even in pre-Cambrian time, and that just as in the Paleozoic era, so in the early pre-Cambrian, marine sediments were deposited mainly on the borders of the shield.[3] Under such conditions the central part of the shield would be a land area and might be undergoing erosion while deposition was in progress on its margin. In support of the second hypothesis it may be noted that the sedimentary rocks of the northern complex are all poorly sorted clastics of the types that are ordinarily deposited by rivers or in shallow lakes, and that the surface rocks of the Timiskaming belt may be terrestrial deposits laid down contemporaneously with the Grenville-Hastings sediments. Evidence that may be cited in support of the third possibility that the Grenville-Hastings series complex is older than the volcanic-sedimentary complex of the Timiskaming geosyncline is that extensive intrusions of igneous rock similar to the gabbro, diorite, anorthosite, etc. of the

[1] Laurentian of some geologists.

[2] P. 314; also *Geological Survey of Canada, Memoir 136*, 1924, pp. 35–39.

[3] M. E. Wilson, *Memoir 108*, 1918, p. 74.

Grenville belt are less abundant or almost wanting in the Timiskaming region, and these in the Grenville belt may be intrusive equivalents of the volcanic extrusions that occur so extensively in the Abitibi (Keewatin) complex. In this case the Grenville series would be older than the Abitibi volcanics. The presence of volcanic flows in the upper part of the Grenville series in the Madoc district also lends some support to this hypothesis. So far as known to the writer, there are no data that would warrant a definite conclusion regarding any one of these three possibilities.

4) In the Timiskaming geosyncline there are numerous belts of sediments part of which, at least, appear to rest unconformably on the Abitibi (Keewatin) volcanic complex and which have been called the Timiskaming series. If it be assumed, then, that the surface rocks of the Grenville and Timiskaming belts are approximately equivalent in age, the erosion interval at the base of the Timiskaming sediments may be the same as that which separates the Hastings from the Grenville series.[1] It may be possible, however, that the apparent presence of a single unconformity in both regions is merely an accidental coincidence of no significance for purposes of correlation. Recent investigation in the Porcupine district, the only locality so far as known to the writer where the structural relations of the Timiskaming sediments to the underlying volcanics have been worked out, shows that the structural discordance is only 20° to 30°.[2] It has been assumed that this pre-Timiskaming unconformity was of major importance because the sediments in some places contain granite pebbles, but it may be possible that the granite pebbles contained in the Timiskaming sediments have been derived from a granite that is older than and not intrusive into the volcanics. The unconformity which separates the Hastings from the Grenville series, as previously pointed out, is a relatively unimportant feature confined to a restricted area in southeastern Ontario. It would seem, therefore, until these unconformities are shown to have a greater importance than is now known to be the case, their correlation is, as yet, only an interesting possibility.

[1] W. G. Miller and C. W. Knight, *op. cit.*

[2] A. G. Burrows, *Canadian Mining Journal*, Vol. XLIV (1923), p. 642. H. S. Robinson, *Economic Geology*, Vol. XVIII (1923), p. 756.

## CONCLUSION

Throughout the Laurentian highlands of southeastern Ontario, southern Quebec, and the Adirondack Mountains of New York State, a highly metamorphosed group of pre-Cambrian sediments known as the Grenville series is extensively developed, and, since rocks of this character are almost entirely wanting in other parts of the great pre-Cambrian shield, this region has been designated the Grenville pre-Cambrian subprovince. Geological field work carried on by the writer in scattered areas throughout the Canadian part of this region—southeastern Ontario and the southern Laurentian highlands of Quebec—has afforded the following information:

1) Except for a few igneous intrusions of lamprophyre, diabase, granite, and syenite, all the pre-Cambrian rocks of this region belong to a basal complex composed of three principal rock groups: (*a*) highly metamorphosed sediments—crystalline limestone, sillimanite-garnet gneiss, quartzite, etc.—with interstratified lava flows in southeastern Ontario—the Grenville and Hastings series; (*b*) a group of igneous rocks, gabbro, diorite, norite, anorthosite, etc.; and (*c*) batholithic intrusions of granite and syenite.

2) In southeastern Ontario the rocks of group (*a*) are divided by an unconformity into two divisions, the Grenville and Hastings series. The deposition of the first of these, the Grenville series, terminated in a period of volcanism and the development of an extended area of land, which underwent erosion for a time before the overlying Hastings series was laid down.

3) In the eastern part of the Grenville subprovince the rocks of group (*b*) form the Buckingham series, an assemblage of igneous types ranging from peridotite to granite pegmatite in composition and containing a pink monoclinic pyroxene as their most abundant ferromagnesian constituent. This series is similar in almost every feature to the Charnockite series of India.[1]

4) The batholithic rocks of group (*c*) occur in granite and syenite phases, the former of which intrudes the latter. The relationships of these intrusives to the Grenville sediments indicate that they

[1] Thomas Holland, *Geological Survey of India, Memoirs*, Vol. XXVIII (1900), pp. 119–249.

underwent deformation during or immediately following their intrusion (Fig. 2).

5) The intrusion of the rocks of groups (*b*) and (*c*) was accompanied by the development of deposits of numerous minerals, among which are amber mica, apatite, magnesite, graphite, feldspar, talc, corundum, magnetite, molybdenite, arsenopyrite, and gold.

A comparison of the formations of the Grenville subprovince with those of other parts of the Canadian shield, and more especially with those of the Timiskaming subprovince, shows that, although many possible relationships suggest themselves, there are, as yet, no data available which warrant positive correlations. For this reason it has been the writer's practice in the Grenville subprovince to avoid the use of the formational names of other subprovinces, such as Algoman, Keewatin, etc., some of which were originally defined in localities hundreds of miles from the Grenville region, and to build up a separate nomenclature for the Grenville subprovince. In case it be desirable to make a correlation of the formations of the Grenville subprovince with those of other subprovinces, or to prepare a table of suggested correlations for the whole of the pre-Cambrian shield, the formations of the Grenville and other subprovinces that are probably equivalent can be grouped together in divisions from which names of local origin are omitted, such as early and late pre-Cambrian, Archeozoic, and Proterozoic, etc. This method of regional classification may seem too indefinite for those geologists who are ever impatient to transform hypotheses into facts, but it is the method which if followed will insure real progress toward that ideal pre-Cambrian classification to which we hope to attain, and will tend to eliminate the confusion that now exists in unraveling the complex history of our great Canadian pre-Cambrian terrane.

# OBSERVATIONS ON THE NORDENSKIÖLD AND NEIGHBORING GLACIERS OF SPITSBERGEN, 1921[1]

GEORGE SLATER

ABSTRACT

The observations recorded in this paper consisted chiefly of measurements of the rate of melting and the relationship of pressure to movement of the ice. A definite relationship was established between the rate of melting of the marginal ice cliffs of the Nordenskiöld Glacier and the air temperature recorded at Bruce City and the Green Harbor Meteorological Station. For each degree Fahrenheit of average maximum monthly air temperature above freezing-point, the amount of retreat of the ice was .5 feet per month, or 5 feet for August, 1921.

The rate of movement of the central crevassed area over a period of 26 days was 51.1 feet, or 1.9 feet per day during August, 1921. In addition to this, directed concentrated pressure was found to produce movement in two directions:

*a*) Movement of névé ice in particular in the direction of pressure along thrust planes associated, in the Sven Glacier, with contortion and imbricate structure.

*b*) Irregular movement or "slide" at right angles to the direction of pressure. The surface of the ice in zones of exceptional pressure was marked by isolated mounds of morainic material which were seen to best advantage on the Sven Glacier.

## INTRODUCTION

In the summer of 1921, I visited Spitsbergen as glaciologist to the Oxford University Expedition. For this opportunity my best thanks are due to my friends, Professor A. M. Carr-Saunders and Mr. N. Odell, leader of the topographical section. Previous observations by Professors E. J. Garwood and J. W. Gregory, and later by Mr. G. W. Lamplugh, clearly show that useful analogies may be drawn between certain phenomena displayed by Spitsbergen glaciers and some types of British drift deposits. I was therefore hopeful that information might be obtained which might possibly throw light upon some of the many complex problems involved in a study of the drift deposits of East Anglia. Such analogies as can be drawn, however, must be local rather than regional. In Spitsbergen, for example, there are local glacial conditions in a more or less mountainous country having a peculiar climate. On the other hand, in East Anglia we have a lowland country which has been inundated by ice

[1] Results of the Oxford University Expedition to Spitsbergen, 1921.

to some extent on a regional scale. Further, the geological structure of the two areas differs in many important respects. To the student of Pleistocene drift deposits, modern glacial studies may be regarded from two standpoints, constructive and destructive. He seeks for information as to the physics of ice movement chiefly as reflected in the disposition and arrangement of morainic material. Englacial material in particular must be arranged according to mechanical and physical laws, whether on a local or regional scale. It follows that if such material is finally preserved, but relatively in its original position, methods of exact measurement may be used in working out the structure. But the varied and complex deposits of Pleistocene drift are also an index of the deglacation of the area in which the original structure in its material in the ice may be either exceptionally preserved in its relatively original position, or, on the other hand, wholly or in part rearranged. This is ultimately a meteorological problem depending on climatic conditions and finally upon the average air temperatures of the area.

Now in East Anglia there are sections in disturbed drift deposits which compare so closely with the arrangement of englacial material in some of the glaciers of Spitsbergen and Greenland as to suggest that the original arrangement of the material when embedded in the ice has been to a large extent preserved.[1] On the other hand, numerous sections in drift deposits show no sign of such structure and suggest an entire rearrangement of the original structure. The two main objects of the present investigation were, therefore, the study of the structure of the ice with special reference to the englacial material, and the conditions of deglaciation.

## THE OXFORD UNIVERSITY EXPEDITION

A brief account of this expedition has already been published in a paper by Mr. R. A. Fraser dealing with the results of the topographical section.[2] Bruce City, at the head of Klass Billen Bay, one of the easternly branches of Ice Fiord, and 1 mile from the Nordenskiöld Glacier, formed the headquarters of the topographical and

[1] See plate of sections, "1907, Excursion to Ipswich," *Proceedings of the Geological Association*, Vol. XX, Part III (1907).

[2] "The Topographical Work of the Oxford University Expedition to Spitsbergen (1921)," *Geographical Journal*, November, 1922.

other sections of the expedition during a stay of five weeks. (See sketch map, Fig. 1.) The choice of the base proved very suitable for glacial study, as it rendered possible the recording of daily observations on one of the most typical and in some respects the most specialized glacier of the country. In addition to this, thanks to the courtesy of Mr. J. Mathieson, of the Scottish Spitsbergen Syndicate, other small glaciers on the other side of the fiord were visited which exhibited sections of considerable interest.

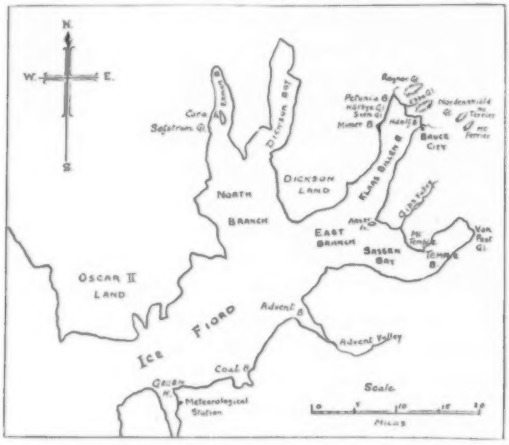



FIG. 1.—Sketch map of Ice Fiord, Spitsbergen

## LITERATURE

The general characteristics of the Nordenskiöld Glacier are well known, and have frequently been described, as it forms a convenient route for exploration parties to the interior. For most of our information, however, we are indebted to the pioneer work of Baron de Geer and his colleagues, extending over many years, resulting in a beautiful map of the glacier published on the occasion of the visit of the International Geological Congress.[1] Further extended observations by Backlund have been published in a memoir dealing with the

[1] Gerard de Geer, "Guide de l'Excursion au Spitzberg," XI Congrès Géologique International, Stockholm, 1910.

results of the Russian Arc of Meridian Expedition,[1] the country being traversed on this occasion from the Nordenskiöld Glacier to Eckmann Bay. More recently, papers dealing with the geology and glaciology of the district have appeared by geologists of the Scottish Spitsbergen Syndicate,[2] including a detailed map by Mr. Mathieson, 1919. Several of these papers deal more especially with the geographical aspects of the glacier, and its bearing on the wider questions of the glaciation of Spitzbergen as a whole. For such work many visits are necessary, as well as abundant facilities for travel. The present investigation was, therefore, confined to a small area near the southwest termination of the glacier, which was easily accessible and displayed the clearest sections. For further work in this area it became clear that trigonometrical work such as has been carried out so successfully by Alpine and other workers would be a necessity.[3]

## THE NORDENSKIÖLD GLACIER

### GENERAL CHARACTERISTICS

As seen from Bruce City, this glacier exhibited a striking spectacle. In the distance, some 6 miles away, rose the two outstanding *nunatakkr* Mounts Terrior and Ferrier, which are approximately 2 miles below the commencement of the gathering-ground of the glacier. Here the glacier is over 6 miles in width, but narrows down to 2 miles at its termination, where the ice forms a partially submerged line of cliffs extending across the deep waters of Adolf Bay. During its journey downward, the glacier is deflected seaward and passes over a buried ridge of metamorphosed rocks. The result of this ob-

[1] Helge Backlund, "Observations dans le Spitzberg Central," *Missions Scientifiques pour la Mesure d'un Arc du Méridien au Spitzberg Entreprises en 1890–1901*, 1908.

[2] J. M. Wordie, "Present Day Conditions in Spitzbergen," *Geographical Journal*, Vol. LVIII (July ,1921), Glaciology, p. 37. G. W. Tyrrell, "Geographical Observations in Spitsbergen, 1919–20," *Scottish Geographical Magazine*, Vol. XXXVII (October, 1921); "The Glaciers of Spitsbergen," *Transactions of the Geological Society of Glasgow*, Vol. XVII, Part I (1919–22); "The Pre-Devonian Basement Complex of Central Spitsbergen," *Transactions of the Royal Society of Edinburgh*, Vol. LIII, Part I (1922), No. 10.

[3] See also A. Hoel, "Observations sur la vitesse d'écoulement et sur l'ablation du Glacier Lilliehöök au Spitsberg," *Vidensk. Selsk.* (Kristiania), Skr. I (1916), Math.–Nat. Kl. No. 4, p. 29.

struction is the formation of an amphitheater of broken ice dissected by two sets of crevasses, forming a central area of rectangular blocks of ice. The moraines may be divided into two series, (*a*) surface moraines, (*b*) marginal moraines.

*a*) *Surface moraines.*—There are six well-marked surface moraines of Alpine character, composed of both angular and rounded erratics. Of these only one, the Terrier moraine, reaches the sea, the other five being stranded against the marginal moraine of the southwest.

*b*) *Marginal moraines.*—These skirt the two flanks of the glacier and consist of "tips" of detritus deposited by the melted ice. They have the appearance of forming a basin-like rim of the glacier from which the ice has shrunk. The most striking of these is the one to the southwest, which attains a height of 80 feet in places, and extends for 3 miles with the regularity of a railway embankment (Fig. 2A.)

Of the stranded surface moraines, the Ferrier moraine is nearest to the sea, but is separated from it by a mile of rounded ice which was the subject of special study.

The main features of the southwest area are as follows: Owing to the wedgelike shape of the glacier, this area has been subjected to exceptional pressure, resulting in the development of movement planes which were well displayed in the cliffs at the termination of the glacier. When the smooth ice of the southwest was followed toward the central crevassed area, its character was seen to change, becoming first undulating and then passing into a series of hummocks aligned along movement planes, and consisting of névé ice, while these, in turn, were dissected by the crevasses of the central area.

### THE FLOOR OF THE GLACIER

The composition of the floor was to be seen in exposures on the northwestern flank of the glacier, the structure of which has been described by Wordie and Tyrell.[1] Other information has been obtained from the petrological study of the bowlders forming part of the southwestern moraine.

[1] G. W. Tyrrell, "The Pre-Devonian Basement Complex of Central Spitsbergen," *Transactions of the Royal Society of Edinburgh*, Vol. LIII, Part I (1922), pp. 209–29.

A.—Moraine bordering the southwest flank of the Nordenskiöld Glacier. (Photo by R. Segnit.)

B.—Line of erratics in Adolf Bay marking the former extent of the Nordenskiöld Glacier.

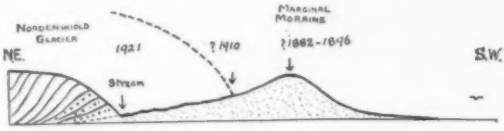
FIG. 2

*Composition of the floor and its bearing on the production of englacial material.*—The floor of the glacier has a fairly steep gradient and consists of hard, resistant rocks of the pre-Devonian basement series associated with igneous rocks, while across the more central part runs a buried ridge of highly metamorphosed rocks. It is from these rocks that the englacial layers forming the lower part of the glacier have been derived. Softer Permo-Carboniferous rocks form the surrounding mountains and furnish material for the surface moraines.

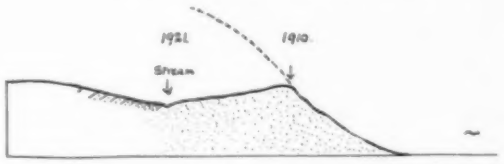
Professor T. C. Chamberlain, in his study of Greenland glaciers long ago, pointed out that such a floor was least favorable for the production of englacial material and the molding of incorporated material along the asymmetrical curves characteristic of glacial tectonics.[1] The amount of englacial material in the basal layers of the Nordenskiöld Glacier is, therefore, small, the thickness of basal detritus averaging not more than 25 feet. A clear section was seen at the southwest termination of the glacier. Here the basal layers rested at a low angle against the slope of the moraine. The layers consisted of fine mud interspersed with bowlders. The under surface of the ice was exposed by a stream and showed well-rounded bowlders partially protruding from the ice. In contrast with these was a large bowlder of syenite, some few feet above the bottom of the ice, which was partially melted out. This was quite angular, its long axis being vertical, and the ice in contact with it showed small contortions. For about a mile extending from the sea to the Ferrier moraine, the englacial layers outcrop along lines running parallel with the moraine. On the surface of the ice the layers appeared as lenticles. Tyrell has shown from a petrological study of the bowlders that this portion of the moraine is composed in great part of englacial material. Examined under a lens, the ice appeared vesicular; and inside the vesicles the mud was in rapid movement. It was also seen to work its way gradually downward. In the process of melting, most of the finer detritus was removed by a marginal stream, only the bowlders being left. Where, however, the stream attained sufficient velocity, the bowlders were removed to lower levels, and then left stranded on the flank of the moraine. With the gradual shrinkage of the ice, this

[1] "Recent Glacial Studies in Greenland," *Bulletin of the Geological Society of America*, Vol. VI (February, 1895).

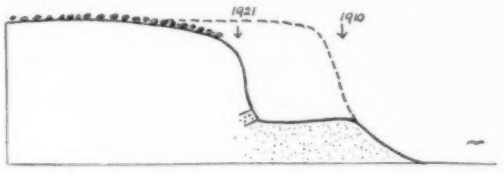
process has been carried on at successively lower levels on the inner slope of the moraine, with the result that gravel is now found at all levels. It was difficult to estimate the amount of material melted out of the ice, but in a selected portion near the southwestern corner where some 20,000 cubic feet of ice was melted out in the month of August, the amount of material deposited was extremely small and




A.—Southwest termination, August 15, 1921




B.—Section 1,100 feet from the sea, August 25, 1921




C.—Section at Ferrier Moraine, August, 1921

FIG. 3.—Sections across southwest moraine of the Nordenskiöld Glacier, 1921

The dotted lines indicate the position of the glacier in 1910. The discrepancy between the rates of retreat of the ice in B and C is due to movement of the ice at C.

took the form of a small heap of rounded bowlders. The three profile sections of the Nordenskiöld Glacier and the southwestern moraine (Fig. 3 A, B, C,) show definitely bedded englacial detritus in the ice on the one side, and a heterogeneous tip heap of morainic matter on the other. The rapid rate of ablation leads to a total destruction of the bedded material in the ice. Under more favorable circumstances the bedded material in the ice might presumably be exceptionally

preserved in its relative position on the windward "iceward" slope of the moraine, but not under the conditions prevailing in this portion of Spitsbergen.

*The northwest side of the glacier.*—The chief interest of the glacier on this "concave" side lies in the portion of the glacier passing over the ridge of metamorphic rocks which are the cause of the crevassing of the central area. The lower bands of englacial material follow generally the outline of the floor beneath. Toward the ridge they curve upward, and are then displaced by the crevasses. In one place, however, the dirt bands assumed a definite asymmetrical curve along the direction of the floor of the glacier, resembling the "drumloidal curve" described by Professor Chamberlin from examples seen in the Greenland glaciers, a type of curve also commonly seen in drift sections of the Norfolk coast. (See sketch, Fig. 4.) It was somewhat disappointing that the actual floor was not exposed in this section. A well-marked marginal moraine flanked the glacier and was definitely associated with the melting out of the lower dirt bands in the ice.

That the lower dirt bands were of universal occurrence was further shown in sections seen in decaying icebergs. When capsized these showed well-maked bands of englacial material occasionally associated with rounded bowlders. As the ice floats down the fiord, these bowlders must be dispersed over a considerable area.

### DEGLACIATION

*Rate of summer melting.*—The rapid rate of melting of the ice was indicated by the volume of water issuing from the glacier and the prevalence of a series of large ice cones, coated with detritus, scattered over the surface moraines. The rate of summer melting appeared, therefore, to be an important factor of what seemed to be a retreating phase of the Nordenskiöld Glacier.

Bearing in mind the possibility of movement in the glacier, it appeared advisable to commence operations by measuring the actual retreat of the edge of the glacier under the conditions of air temperature then prevailing.

The most suitable position for such measurements was at the extreme southwest corner of the glacier adjoining the sea. Here the

marginal ice cliffs formed a right angle, the seaward cliffs facing northwest, the other side facing the southwest and the long frontal

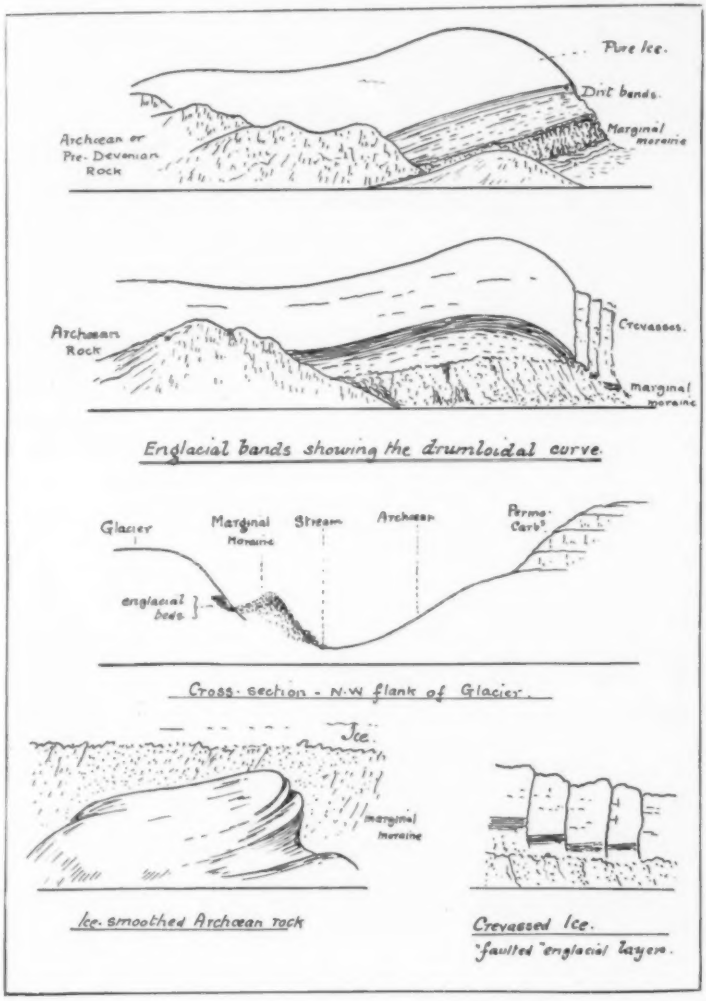



FIG. 4.—Sketches on the northwest side of the Nordenskiöld Glacier, 1921

A.—Nordenskiöld Glacier, southwest termination. The photo shows inclined englacial material. The rate of the retreat of the ice face was measured here. (Photo by R. Segnit.)

B.—Nordenskiöld Glacier, southwest flank. Bands of englacial material outcropping parallel to the marginal moraine, seen in the foreground. (Photo by G. Slater.)

FIG. 5

moraine. Near the corner of the two was a large bowlder against which was erected a pole (Fig. 5). These cliffs had the great advantages of being protected from the wind and from an accumulation of seasonal snow.

The cliffs facing northwest were of considerable height and were usually undercut by the sea. A portion of the ice, however, was beyond the reach of the tides and rested on a low, sloping beach. All the cliffs of this portion had an upper overhanging cornice. In one place the cliffs were fronted by a gravel mound. It was at this point that the measurements were taken. Upright posts were erected in the gravel, and a peg was driven into the ice at some distance from the edge on the upper surface of the glacier and protected from melting. A line fastened to this peg was hung over the cliff and suitably weighted so as to hang taut but without cutting into the upper cornice of the cliff. Measurements were then taken from the nearest post to the suspended plumb line, and again from the plumb line to the undercut surface of the ice (Fig. 6).

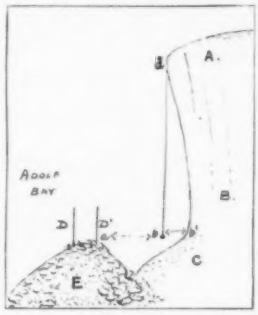



FIG. 6.—Southwest termination of the Nordenskiöld Glacier. Ice cliffs facing northwest aspect seaward.

(Station IV of Table I, of "Rate of Retreat of Ice.")

*AB*—cliff of pure ice, height about 40 feet.

*C*—ice containing englacial material.

*E*—heap of frozen gravel, loose bowlders on the surface.

*D*, *D'*—measuring-posts

*bd*—plumb line

*ab*—distance measured

*bb'*—undercut of cliff. This distance remained nearly constant.

The upper ice *AB* was pure, the lower ice *C* contained englacial material in its lower portion. The stakes *D*, *D'* were tested daily and sighted from fixed points to insure that stability had been maintained (Fig. 7). The posts *D*, *D'* (Fig. 6) were used to check the position of the plumb line. They proved that there was no movement toward the southwest, that is, toward the marginal moraine.

The original distance *ab* from the pole *D'* to the plumb line was 9 feet 8.5 inches. (See Table I.) The results obtained at this station are dealt with later, as they proved that movement of the ice had

occurred in a direction *toward* the posts $D$, $D'$, but *not* at right angles to that direction.

It is sufficient here to mention that by August 25, 1921, the ice had retreated only 1 foot 1.5 inches (Table I, Station IV), the dis-

TABLE I

NORDENSKIÖLD GLACIER, 1921: RATE OF RETREAT OF ICE NEAR ADOLF BAY

| DATE | FACING SOUTHWEST | | FACING NORTHWEST | |
|---|---|---|---|---|
| | Station I* | Station II | Station III | Station IV* |
| | ft. in. | ft. in. | ft. in. | ft. in. |
| July 29 | ..... | ..... | 0 | ..... |
| July 30 | ..... | 0 | 1.5 | ..... |
| July 31 | ..... | ..... | 6 | ..... |
| August 1 | 0 | 5.5 | 8 | 9 8.5 |
| August 2 | 4 | ..... | ..... | ..... |
| August 4 | 6 | ..... | 1 0 | 9 9 |
| August 5 | 8 | 1 0 | 1 2 | 9 11 |
| August 7 | ..... | ..... | ..... | 9 11 |
| August 8 | ..... | ..... | 1 6 | ..... |
| August 10 | 1 6.5 | 1 7 | 1 10 | 9 11 |
| August 15 | 2 1 | 2 2 | 2 2.5 | 10 4.25 |
| August 22 | 3 7 | 3 6 | 2 11 | 10 9 |
| August 25 | 3 11.5 | ..... | 3 1.5 | 10 10 |

* The marked discrepancy between the records in columns I and IV is due to movement at Station IV.

Total amount of retreat:

Station I. For 24 days, 3 feet 11.5 inches or 2 inches per day = approximately 5 feet per month.

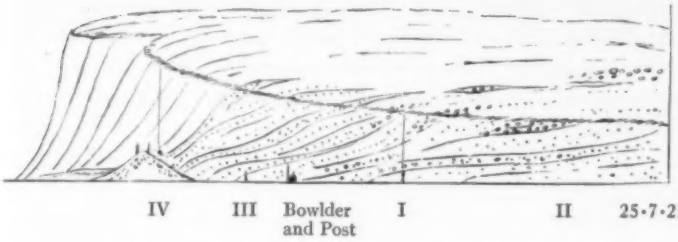
Station II. For 23 days, 3 feet 6 inches or 1.8 inches per day = approximately 4 feet 8 inches per month.

Station III. For 27 days, 3 feet 1.5 inches or 1.4 inches per day = approximately 3 feet 7 inches per month.

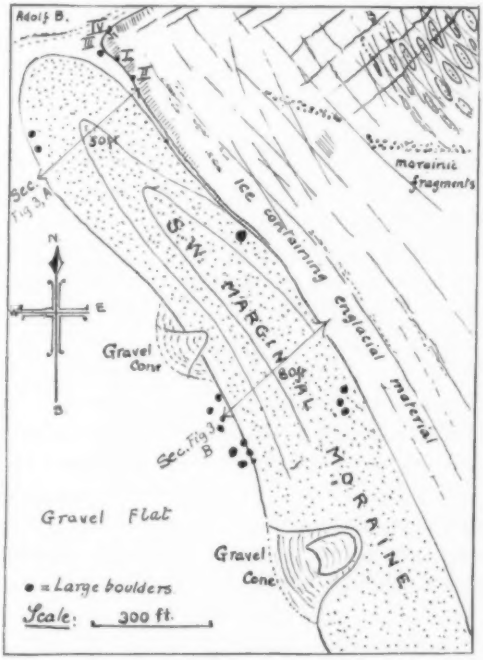
Station IV. For 24 days, 1 foot 1.5 inches.

tance from the post to the plumb line being then 10 feet 10 inches and from the plumb line to the undercut ice 6 feet 2 inches. The total distance, therefore, from the post $D'$, to the nearest ice was 10 feet 10 inches + 6 feet 2 inches = 17 feet.

I am indebted to my friend Dr. T. G. Longstaff, who was a member of the 1923 Merton College Spitsbergen Expedition, for measurements taken August 30, 1923, from the gravel mound to the nearest portion of the ice. His measurement taken from the approximate position of the posts $D$, $D'$, which had then fallen but were lying on




A.—Southwest termination, showing positions of stations




B.—Southwest marginal moraine

FIG. 7.—Nordenskiöld Glacier, 1921

the top of the mound, was 29 feet 3 inches to the nearest ice of the glacier, or an increase of 12 feet for the two years. In addition to this 12 feet, however, the ice between the upright post near the large bowlder, and the gravel mound had also been melted, but this distance was not measured.

The additional photos taken in 1923 showed that in spite of the melting of the ice, the relative distance of the ice cliffsto the sea has not greatly changed, pointing to compensation by movement seaward as being a constant factor in the physics of the glacier.

At the cliffs facing southwest, two horizontal posts weighted by stones were placed near the ice, Station I of Table I being 38 feet from the upright post near the bowlder, and Station II 95 feet from it (Fig. 7). Station I proved the most suitable position. The post was a flat one resembling a railway sleeper, and had two uprights, to which were fastened a rod which actually touched the ice at the commencement of the experiment. This rod extended about a foot beyond the lower edge of the post. The results obtained at these stations are shown in Table I. Additional measurements were also obtained from the corner of the ice cliffs called Station III.

Measurements of the melting of the ice on the top or upper surface of the ice some distance from the end of the glacier were recorded for eleven days only, from July 30 to August 10, and indicated a decreased rate of melting of 1.25 feet for that period, or about 1 meter for a period of twenty-nine days, apparently due to the angle of inclination of the sun's rays on the surface of the glacier, and the lower air temperature above the ice. Hoel's figures for the ablation of the Lilliehöök Glacier August 3–30, 1909, at three stations are 0.70, 0.89, and 0.79 meters, but he gives no record of temperature.

*Rate of retreat of the ice cliffs. Summary of results.*—The cliffs facing southwest contained englacial material. The results obtained from Station I are the most favorable for forming an estimate of the rate of retreat of the cliffs, owing to its suitable position. Column 1 of Table I shows that the measurements were continued for a period of twenty-four days. The average rate of melting was 2 inches per day, or approximately 5 feet for the month of August.

In order to ascertain whether any movement was taking place, two plumb lines were suspended from the top of the ice cliffs, one at

Station I, the other at right angles to this, at Station IV near the heap of gravel already described (Figs. 6 and 7 A). These lines gave no indication of movement toward the southwest, and hence the figures of column 1, Table I, represent absolute rates of melting ice under the conditions of air temperature prevailing at the time.

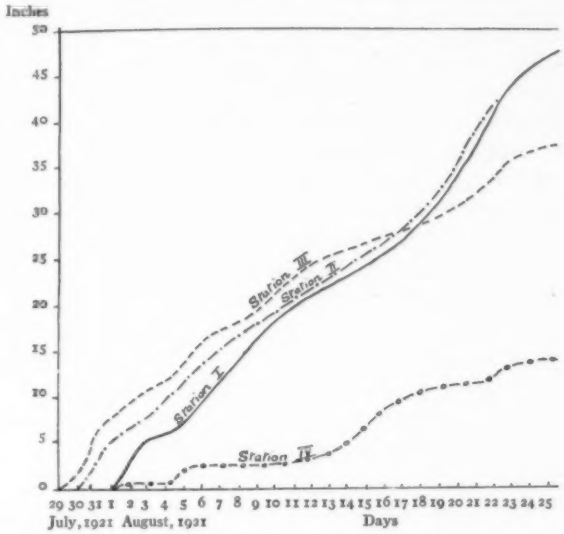



FIG. 8.—Nordenskiöld Glacier, 1921. Graph showing rates of retreat of the marginal ice cliffs near Adolf Bay.

The results obtained from Station II generally support those of Station I, making allowance for the less favorable position of Station II relative to the rays of the sun.

At the cliffs facing northwest, the measurements at Station IV were taken from posts erected in the gravel heap to the suspended plumb line (Fig. 6). The amount of undercut was also measured. The results obtained will be treated in detail when movement of the ice is discussed. It is sufficient here to state that the measurements proved that the decay of the ice cliff due to melting was here compensated to some extent by the moving seaward of the ice, that is, toward the northwest at this point. The graph (Fig. 8) shows that

cessation of movement occurred at intervals, proving that the rate of melting at Station IV did not differ markedly from that of Station III.

*Air temperature.*—A number of preliminary measurements of the rate of melting of the ice were made at different times of the day. These pointed to the close connection of melting with the air temperature, and the position of the ice relative to the inclination of the sun's rays. A certain lagging effect due to the latent heat of water was noticed. The rate of melting was generally greatest in the afternoons, but melting occurred during the whole period of the twenty-four hours, owing to continuous exposure to the sun. Records of air temperatures were taken with a screened thermometer at Bruce City from July 22 to August 25, with, unfortunately, a break of eight days of bright sunshine during the first week of August. These records gave an average daily temperature of 44° F., or, for the nineteen days of August, of a little over 43° F.

The daily records of temperature taken at the Green Harbor Meteorological Station during August, 1921, also gave an average temperature of between 43° and 44° F.

The similarity between the two sets of records appeared to justify the use of the daily records of temperature taken at Green Harbor between the years 1912, when the station was established, and 1921, as a basis for estimating the rate of retreat of the southwest portion of the glacier over a period of years. For this purpose the table of temperatures is given for the period 1912—21, (Table II) while Table III gives the average air temperatures for 1922–23. As Table II shows, the average *maximum* daily temperatures do not differ very much from the average air temperatures at 15 hours (=3.P.M.), but exceed the mean (hourly) temperatures by about 2° F. In the last column, the average temperatures for June and September are too low for the purpose of estimating the rate of melting, as the temperature usually fell below freezing-point in the early hours of the morning. The third column (average maximum daily temperatures) has therefore been adopted for estimating the relationship between the melting of the ice and air temperatures.

Taking the maximum air temperature in the neighborhood of the Nordenskiöld Glacier as about 10° F. above freezing-point for the month of August, we get the following relationship:

For an average monthly maximum temperature of 10° F. above freezing-point, the ice face was melted back 5 feet. Therefore for 1° F. the amount melted per month would be .5 feet, taken as a first approximation.

TABLE II

AIR TEMPERATURES FOR YEARS 1912–21 INCLUSIVE, GREEN HARBOR METEOROLOGICAL STATION, SPITSBERGEN*

| PERIOD | TEMPERATURES AT 15 HOURS (=3 P.M.) | | AVERAGE MAXIMUM DAILY TEMPERATURES | | MEAN HOURLY TEMPERATURES | |
|---|---|---|---|---|---|---|
| | C. | F. | C. | F. | C. | F. |
| June | 3.00° | 37.40° | 3.20° | 37.76° | 1.74° | 35.14° |
| July | 5.92 | 42.65 | 5.982 | 42.76 | 4.92 | 40.85 |
| August | 5.289 | 41.52 | 5.383 | 41.689 | 4.18 | 39.52 |
| September | .02 | 32.03 | .8 | 33.4 | −.71 | 30.72 |

* *Jahrbuch des Norwegischen Meteorological Institute*, and Meteorological Office daily weather report, July to September, 1921.

TABLE III

AIR TEMPERATURES (FAHRENHEIT), 1922–23, GREEN HARBOR METEOROLOGICAL STATION, SPITSBORGEN*

| Period | 1922 | 1923 | Totals | Mean |
|---|---|---|---|---|
| June | 39.10° | 36.00° | 75.10° | 37.55° |
| July | 46.66 | 44.00 | 90.66 | 45.33 |
| August | 43.40 | 42.10 | 85.50 | 42.75 |
| September | 36.26 | 35.80 | 72.06 | 36.03 |

* From the Meteorological Office daily weather report. Air temperatures (the mean of three readings), and therefore approximating more nearly the maximum temperature than the hourly mean temperature.

To apply this relationship, therefore, it is only necessary to divide the average maximum number of degrees Fahrenheit above freezing-point by 2 for each of the summer months to obtain the amount of ice melted back. (See Table IV).

This relationship is indicated by the formula:

$$M = \frac{t^\circ - 32\ \mathrm{F}}{2}.$$

where $M$ = amount in feet of ice melted per month, and $t^\circ$ = average maximum monthly temperature (F.°).

Table IV gives an average yearly rate of retreat of the edge of the ice of 13.8 feet, or 14 feet approximately.

TABLE IV

APPLICATION OF THE RELATIONSHIP BETWEEN AIR TEMPERATURES AND RATE OF MELTING OF THE ICE, 1912–21

| Period | Average Maximum Temperatures (Fahrenheit) | Amount above Freezing-Point (Fahrenheit) | Amount of Ice Melted Back per Month (Feet) |
|---|---|---|---|
| June | 37.76° | 5.76° | 2.8800 |
| July | 42.7676 | 10.7676 | 5.3838 |
| August | 41.6894 | 9.6894 | 4.8447 |
| September | 33.4 | 1.4 | .7 |
| Total | | | 13.8 |

Confirmatory evidence as to estimated rate of retreat of the Nordenskiöld Glacier is as follows:

In 1910 the ice of the Nordenskiöld Glacier was resting on the crest of the long frontal moraine shown on Figure 2 A. This is well shown in the photograph by Baron de Geer[1] and also in another illustration by the late Professor Grenville Cole.[2] The position in 1910 is indicated by a dotted line on the plate of profile sections. (Fig. 3B. See map, Fig. 7, for position.) The three profile sections were all carefully drawn to scale. Figure 3B, at 1,100 feet from the sea, is approximately in the same position as the portion photographed by Professor Cole (Fig. 7). In 1921 the edge of the ice was 158 feet from the crest of the moraine. This represents the amount of retreat in eleven years, giving an average of 14.3 feet per year.

Dealing now with the temperatures 1922–23, we get the results shown in Table V.

This estimate may be checked as follows:

Station I (Fig. 7 A) was 3 feet 11.5 inches from the ice on August 25, 1921. This was measured from a projecting rod fixed to an upright planted in a horizontal beam heavily weighted with stones. The edge of the beam was 5 feet from the ice at this time (August

[1] *Op. cit.*, Taf. 4.

[2] G. A. J. Cole, "Glacial Features in Spitsbergen in Relation to Irish Geology," *Proceedings of the Royal Irish Academy*, 1911, 29 B, pp. 191–208.

25, 1921). At the fairly constant rate of melting at the time of about 2 inches a day, we may fairly assume that the distance of the beam from the ice by the end of August would be 6 feet.

Dr. Longstaff kindly measured the position of the ice from this station August 30, 1923, at 2 A.M. The ice was 39 feet 3 inches from the edge of the lower beam, showing a retreat of 33 feet 3 inches during the last two years.

TABLE V

APPLICATION OF THE RELATIONSHIP BETWEEN AIR TEMPERATURES AND RATE OF MELTING OF THE ICE, 1922–23

| Period | Average Temperature (Fahrenheit) | Amount above Freezing-Point (Fahrenheit) | Amount of Ice Melted Back per Month (Feet) |
|---|---|---|---|
| 1922: | | | |
| June | 39.10° | 7.10° | 3.55 |
| July | 46.66 | 14.66 | 7.33 |
| August | 43.40 | 11.40 | 5.70 |
| September | 36.26 | 4.26 | 2.13 |
| Total | ..... | ..... | 18.71 |
| 1923: | | | |
| June | 36.00 | 4.0 | 2.0 |
| July | 44.00 | 12.0 | 6 |
| August | 42.10 | 10.0 | 5 |
| September | 35.80 | 3.8 | 1.9 |
| Total | ..... | ..... | 14.9 or 15 |
| Total 1922–23 | ..... | ..... | 33.61 |

*Marine ablation of the glacier.*—Ablation of the sea is far in excess of the wastage on land and is indicated on the maps by de Greer, 1910, and Mathieson, 1919–21. The wastage is greatest near the maximum subglacial drainage. The melting of polar ice has been investigated by Nansen on a regional scale, but we are here more directly concerned with the melting of the ice in the upper, warmer layers of the sea. There are three main factors contributing toward the rapid rate of marine ablation: *a*) the undercutting of the ice by the sea; *b*) the hydrostatic leverage by the tides of the rectangularly crevassed blocks; *c*) the concentration of subglacial drainage. With these may be associated the latent heat of the sea water acting over a longer period than melting by air temperature.

The rapid wastage of the ice in Adolf Bay relative to the wastage on land was shown by the horseshoe outline of the ice in the southwest and the frequent falls of the sea cliffs when undercut by the sea (Fig. 9, A, B).

The position of concentration of subglacial drainage appears to vary. In 1921 it was nearer the southwest side, and torrential falls of ice at this place were of daily occurrence. The rate of decay of the ice cliffs has varied considerably in different parts of the glacier during past years, and is shown on the map (Fig. 10), but over a series of years an approximate yearly average can be deduced.

The general results of marine ablation are given in Table VI, the figures indicating a considerably accelerated rate of melting during recent years.

TABLE VI

MARINE ABLATION OF THE NORDENSKIÖLD GLACIER

| Years | Average Rate per Year (Feet) |
|---|---|
| 12 (1896–1908) | 41* |
| 13 (1908– 21) | 138† |
| Rate of increase, 41:138 or 1:3. | |
| | Maximum Retreat (Feet) |
| 12 (1896–1908) | 656* (or 100–200 meters) |
| 11 (1908– 19) | 800 |
| 2(1919– 21) | 1400 |

* deGreer.
† Mathieson.

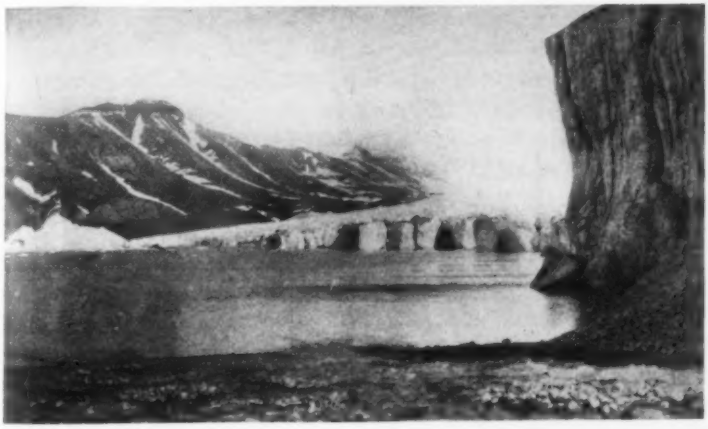
A well-marked line of erratics in Adolf Bay marks a former stage in the history of the Nordenskiöld Glacier (Fig. 2 B).

The main conclusion derived from the study of the melting of the ice is that marine ablation is approximately ten times greater than the melting of the ice by temperature only.

*Hoel's work on the ablation of the Lilliehöök Glacier compared with the observations on the Nordenskiöld Glacier, 1921.*[1]—Before concluding the subject of the deglaciation of the Nordenskiöld Glacier it will be necessary to refer in greater detail to the work of Hoel on the rate of ablation of the Lilliehöök Glacier of Spitzbergen, which appears to be the only other published work on the rate of melting of a

[1] *Loc. cit.*

Spitsbergen glacier. The method adopted in the present investigation of measuring the rate of melting from the marginal cliff of the



A.—Nordenskiöld Glacier. Sea cliffs, July, 1921. (Photo by Dr. Longstaff.)

B.—Nordenskiöld Glacier. Sea cliffs, July 31, 1921, after the fall of the cliff shown in A, righthand side. (Photo by Dr. Longstaff.)

FIG. 9

glacier, where the ice was proved to be stationary, differs essentially from that of Hoel, who adopted the usual method advocated by

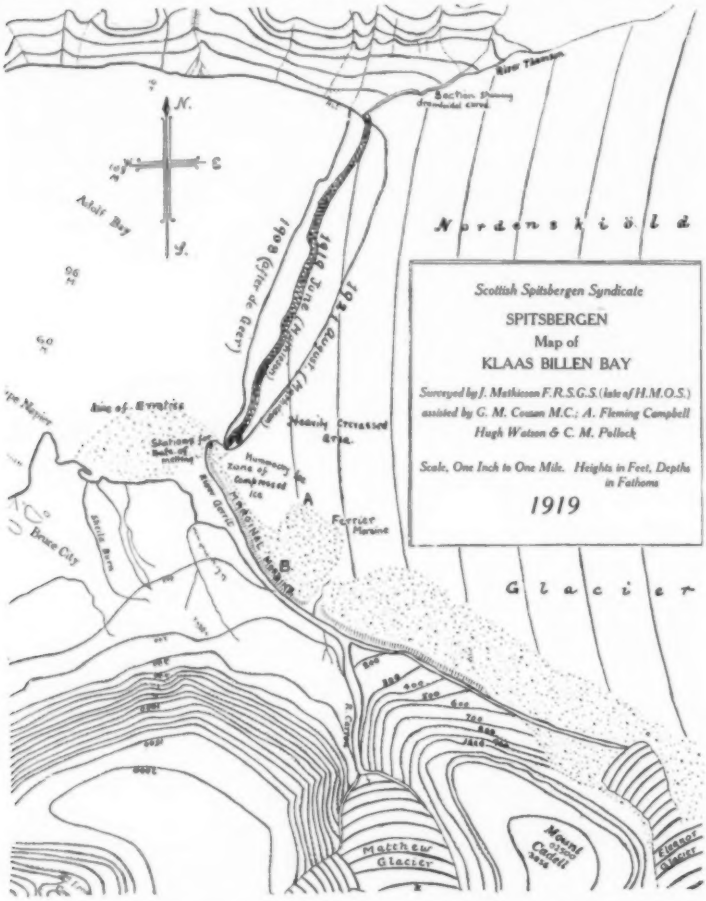



FIG. 10.—Map of the termination of the Nordenskiöld Glacier, 1919. Reproduced by kind permission of the Scottish Spitsbergen Syndicate, through the courtesy of J. Mathieson, Esq.

Hamberg of measuring the rate of melting of the *surface* of the ice from fixed posts inserted in the glacier at various altitudes.

Taking Hoel's most suitable station, the amount of ablation for twenty-seven days (August 3–30, 1909) was .79 meters at an altitude of 55 meters or 400 meters below the snow line. This gives an approximate amount of melting for eleven days of .32 meters, or about 1 foot.

During the investigations of 1921, I only measured the rate of melting on the surface of the Nordenskiöld Glacier for eleven days (July 30–August 10, 1921) of bright sunshine at a point near the southwest termination of the glacier and having an altitude of about 20 to 30 meters. The amount of ice melted was .38 meters, or 1.25 feet. Taking into account the difference in altitude between the two stations and a possible difference in average temperatures, the discrepancy between the two estimates is not serious, and leads to the assumption that the rate of melting of a large portion of the lower portions of both glaciers would be about 1 inch a day, or approximately 2.5 feet for the month of August, a rate of melting about half that of the marginal cliffs of the Nordenskiöld Glacier in 1921 for the same month.

This discrepancy may be accounted for by various factors, of which the following would appear to be the most important: (*a*) the lower air temperature above the surface of the glacier; (*b*) the angle of inclination of the sun's rays on the surface of the ice; (*c*) absence of radiation of heat from the ground; (*d*) exposure of the surface to the wind. Further observations by Hoel, extending over longer periods, gave the following results:

Station $F_1$ (July 28, 1907–August 5, 1909), rate of melting 2.0 meters.
Station $F_1$ (August 30, 1909–July 30, 1910), rate of melting 1.71 meters.

He estimates the rate of melting per annum as 1.40 meters. This figure is not quite double the rate of melting measured by him for the month of August. This estimate cannot represent the total annual amount of melting, as the heat from the sun during the month of June would be utilized in melting the accumulation of seasonal snow. Such an accumulation would not occur on the marginal vertical cliffs of the Nordenskiöld Glacier.

The position of the ablation station selected by Hoel, at an altitude of 400 meters below the snow line, is in accordance with the work of Hess correlating the amount of melting at this level with the

latitude. The relation between altitude and rate of melting has also been investigated by Drygalski for Greenland glaciers, and the relationship is further illustrated by examples taken by Hoel from various latitudes.

While admitting the value of these observations, this method of correlation appears to be only a circuitous method of correlating rate of melting with air temperature.

By the application of the tentative law of ablation given in the present paper it is possible to form an estimate of the mean temperature of the air at Hoel's stations for the month of August. This would appear to have been between 37° F. and 38° F., but unfortunately there are no records of the actual temperature which would enable these figures to be verified.

It would, therefore, appear to be desirable that in future observations on the rate of melting of the ice, records of air temperature should be taken as well.

The results of the present investigation support the view that the true rate of shrinkage of a glacier can be most accurately ascertained by measurements on the flank of the glacier at stations where it can be proved that the ice is stagnant, and that this rate of shrinkage bears a direct relationship to the average monthly air temperature during the summer months.

### STRUCTURE OF THE ICE IN THE SOUTHWEST

*The sea-cliffs.*—The usual phenomena associated with compressed ice were well shown in the ice cliffs bordering the sea near the southwest termination of the glacier. The lower layers of ice, containing englacial material, rested on the inner or iceward flank of the moraine and were succeeded by stratified bands of pure ice dipping toward the center of the glacier at a gradually increasing angle, until the inclination became almost vertical toward the more central part of the glacier. (Figs. 5 A, B, and 9 A, B). When freshly exposed, the ice was of a blue color but on exposure became white, and the softer division planes were etched out. The granular structure was best displayed in the ice floes stranded on the shore. The lines of parting between the layers of ice are described in this paper as "movement planes" and are the direct effect of pressure.

*The surface of the ice between the sea and the Ferrier moraine.*—The ice in this area had a rounded surface discolored by surface dust, and sloped downward to the moraine. The bands of englacial material were lenticular in form and the outcrop ran parallel to the edge of the ice and the marginal moraine until within a short distance of the Ferrier moraine (Fig. 5 B). A little farther up the slope of the ice, other movement planes in pure ice occurred, a strong set parallel to the englacial layers, and a weaker set with a slightly different trend. As the ice was traced upward, incipient crevasses at right angles to the movement planes began to appear, and the surfaces of the ice assumed a wavy appearance. By the intersection of these cracks and the movement planes, the ice was divided into a series of rectangular cracks. In one part a long line of angular surface débris had been displaced some distance by one of these isolated masses, giving the appearance of an outcrop of rock displaced by a dip fault. It was only along the marginal sea cliffs, however, that crevasses were conspicuously developed (Fig. 7 B).

*The zone of hummocky ice.*—An interemdiate zone of hummocky névé ice occurred between the boundary of the central crevassed area and the smooth rounded ice of the southwest. The size of the hummocks varied; in the neighborhood of the crevasses they attained a height of from 10 to 15 feet, but decreased in size toward the southwest, this type of ice ending as wavelike undulations on the one side and passing into crevassed ice on the other. The hummocks were arranged in a definite manner, the long axes as a rule being aligned along the direction of the resultant of two sets of movement plans (Fig. 11). In outline each hummock formed an asymmetrical curve with a gentle slope on the windward (or iceward) side directly exposed to thrust, and a steeper slope on the protected or leeward side. The upper portion of each hummock consisted of white, loose granular ice full of interstitial air, but the lower part was composed of hard blue ice and rested on an inclined thrust plane. That an upward motion was taking place along the lower dominant thrust planes was shown by the squeezing up of the superficial surface dust, forming cylindrical lines of dirt sometimes resembling worm casts. The thrust planes were not confined to the lower layers of the hummocky ice, but also occurred to a less extent in the upper part, resulting in

the production of a slight overhanging cornice. These latter thrust planes were superficial, contrasting strongly with the major thrusts, which are deep seated.

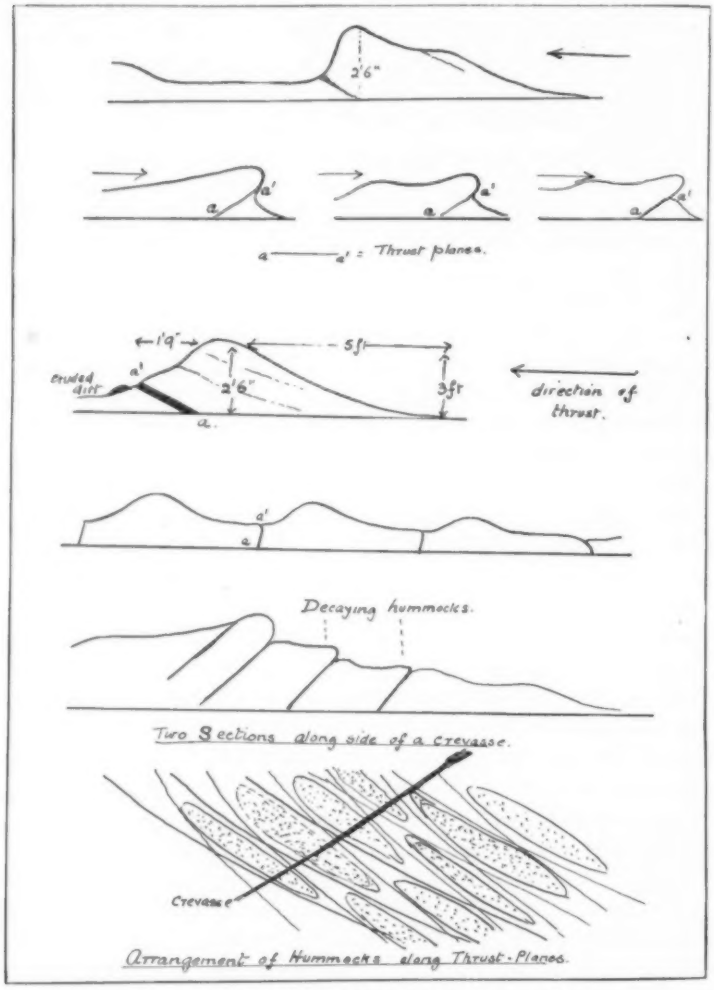



FIG. 11.—Nordenskiöld Glacier. Sections of hummocks

In places the hummocks had been neatly cut across somewhat longitudinally by crevasses. When such crevasses were freshly made, the sections of the hummocks were very clear, but the effect of the dissection of the hummocks was soon apparent by their loss in size. Hence the hummocks formed by pressure were formed first, the crevasses due to tension occurring later.

It seems apparent that the two sets of thrust planes were formed at different periods, the one set being deep seated, the other series being superficial. Again, the crevasses are not always at right angles to the alignment of the mounds. For example, in a selected group the crevasse had a direction E.15°N., or roughly east-west, and the alignment of the mounds was NE. 15° N., or roughly northeast-southwest. The crevasses which extend downward to a considerable distance are at right angles to the deep-seated movement planes. These movement planes are due to the pressure of the glacier as a whole, while the superficial thrusts represent a later pressure due to superficial "waves" of névé ice (Fig. 11).

As regards direction of the thrust planes, in a selected series one line of thrust lined on either side by hummocks ran S. 10° E., or roughly North–South, but was not straight. Another one 50 feet away ran S.35° E., and there were three series of hummocks between; one hummock was 14 feet long and the angle of the thrust plane was 40°, while the heap of exuded clay extended 6 feet. Ice cones sprinkled with similar clay were common and quite large, but one small one situated on a "crack" was sprinkled with mud and was 10 feet long, 4 feet wide, and 2 feet high.

One of the most interesting lines of hummocks was aligned along a curving thrust plane whose direction formed a concave line varying in direction from S. 38° E., S.45° E., S.48° E. to E. 30° N., and had a total length of over 600 yards.

It seems clear that the major thrusts have an alignment approximately from Northwest–Southeast in the Southwest part of the glacier, which is the part specially dealt with here, but the direction varies elsewhere according to the shape of the glacier basin and direction of pressure. The orientation of the second series varies, sometimes making a small angle, at other times making a large angle with the other lines of thrust. The relationship of these movement planes

to the sharp curve of the Ferrier moraine is interesting. At the curve of the moraine (Fig. 10 A), the thrust planes pass across the moraine, and the series have a radiating arrangement. In cross-section this part of the moraine assumes the form of a series of small overthrusts, the surface moraine rising along a series of gradually ascending ridges toward the crest of the moraine near its southwestern termination. Here the phenomenon is replaced by a sinuous line of morainic material obviously associated with the ordinary flow of an unimpeded ice sheet (Fig. 10 B).

The bearing of these facts on the change of the direction of the glacier is dealt with at a later stage when discussing the Ferrier moraine.

### MOVEMENT OF THE GLACIER

*Movement of the central crevassed area.*—The rate of movement of the central crevassed area was determined by Mr. J. Mathieson by means of a theodolite over a period of twenty-six days. During this time the ice moved 51.1 feet, or 1.9 feet per day during August, 1921. The theodolote was sighted on a well-marked crevasse which maintained its form during the period of observation. The observations were made from a trigonometrical point in the neighborhood of Bruce City, and the distance of the point observed was probably between 1 and 2 miles.[1]

*Movement in the southwestern area.—observations at the sea cliffs.*—The rounded mass of ice in the southwest, resembling the expanded foot of a stagnant glacier, had every appearance of "dead ice." It was certainly an embayment of ice out of the main flow of the glacier. It also consisted of ice under pressure, as shown by the structure. The measurements of the rate of retreat of the overhanging cliff of ice at Station IV (Fig. 6) deserve special attention. The adjoining cliffs rested on a beach which was covered by the sea at high tide. These cliffs showed considerable undercutting, and very heavy falls occurred at frequent intervals (Fig. 9 B). The cliffs at Station IV also rested on a beach, but the base was above the reach of the sea. Here the lower part of the cliff projected as a low mound, the base of the cliff being composed of ice containing englacial material.

[1] See also Hoel's work on the Lilliehöök Glacier.

Measurements were taken from fixed posts in the adjacent gravel mound to the plumb line suspended from the overhanging cornice (Fig. 6). A reference to Table I shows that in twenty-four days the cliff had retreated a little more than a foot, and that for nearly a week the distance of the plumb line from the post remained constant in spite of continuous melting. At other times, as will be seen from the graph (Fig. 8), the rate of retreat bore some resemblance to that at the other stations. The amount of undercut of the cliff at the beginning and end of the observations was about the same (Fig. 6, *bb'*). One feels justified in assuming, therefore, that the whole cliff was intermittently sliding over the basal ice at the same rate as the rate of melting. It is, therefore, probable that some slight movement seaward was also taking place at Station III. The ice at the southwest termination of the glacier has remained at approximately the same distance from the sea over a long period, and this is borne out by a consideration of the maps by de Geer and Mathieson, where the southwest point of the glacier has been regarded as stationary for trigonometrical purposes. Hence retreat of the ice due to melting of the cliffs facing northwest has been compensated by proportionate movement seaward.

This raises the question of ice movement under pressure and revives the rival theories of De Saussure, who advocated sliding (also advocated by Hopkins), and James D. Forbes, who advocated the motion of ice as a plastic body and the regular continuity of glacier motion.

Forbes selected for his experiments compact ice devoid of open fissures, showing veined structure, but having no crevasses.[1] Under these conditions he proved that ice had a regular ordered rate of movement.

Now, although the original theory of "slide" as applied to glacier motion is inadequate to explain glacial motion as a whole, yet the present observations appear to suggest that it is applicable to special areas subjected to exceptional directed concentrated pressure.

In the compressed area studied in the Nordenskiöld Glacier, the longitudinal movement planes were frequently open or were such as to enable one to drive in wooden pegs with ease. Incipient crevasses

[1] The Theory of Glaciers (1859), p. 104.

were seen to work their way into the margins of the compressed area daily, and the intersection of these with the longitudinal fissures gave rise to individual blocks of ice of rectangular shape, from 20 to 30 feet in length. These blocks suggested individual movement. The faulted line of morainic fragments also supports the view of isolated differential motion in the compressed area, of a type similar to that of the marginal sea cliffs (Figs. 6 and 7B).

Under these conditions, motion by slide appears to be suggested by the facts, but this type seems to be restricted to special zones. Motion by slide appears to have a definite relationship to the amount of pressure, and is assisted by lubrication due to melting; it also compensates loss of the marginal cliffs due to melting. Relief from pressure by tension was shown by the presence of crevasses bordering the marginal cliffs, which have been proved to be moving at an irregular rate.

### THE FERRIER MORAINE

The peculiar termination of the surface moraines is well shown on de Geer's map and has been explained by him as due to the effect of a stream of ice emerging from a tributary glacier. This tributary ice stream, however, has been separated from the Ferrier moraine for some years by a wide hollow drained by a stream and shown on Mathieson's map (1919). This area contained many rounded bowlders of considerable size, which appeared to have been melted out of of the lower layers of the ice. We may, therefore, regard the Ferrier moraine as an independent unit. Near its termination this moraine was situated on a mound of ice much higher than the general level of the glacier. The morainic material formed a very sinuous ridge, and fanned out and terminated on the top of a cliff of discolored ice over 100 feet high, which rested in a hollow of the long marginal moraine.

Tyrrell has shown that the rocks associated with the Ferrier moraine have a distinctive character and form a suite which does not occur to any appreciable extent in the marginal moraine composed of englacial material which extends from this point to the sea. Again, the distance of the ice cliff from the crest of the marginal moraine upon which it rests is only 115 feet, or less than the average distance

elsewhere. That ice occupied this hollow in 1910 appears clear from de Geer's photograph. We may reasonably conclude, therefore, that the hollow in the marginal moraine marked the position of the outlet of the ice in this part of the glacier, and had done so for many years; that is, that the general direction of flow of the ice of the glacier had been deflected to the southwest. This marked change in direction appeared to be due to the structure of the ice in the compressed area between the Ferrier moraine and the sea. The faulted line of morainic fragments in this area appeared to show that ordinary movement of ice simulating flow structure may occur to a small degree under certain conditions in the compressed zone, but sooner or later becomes replaced by movements of another type. Hence the compressed zone of ice has acted as a horst to the moving layers, causing deflection of the Ferrier moraine on the one side, and overthrusting of névé ice on the other. Relief from pressure occurred along the marginal cliffs bordering the sea and was shown by the crevasses running parallel to the edge of the cliffs. The measurements showed that the compressed pure ice was moving over the stagnant lower layers of dirt-filled ice. This point was exemplified still better in the Sven Glacier.

### THE EBBA GLACIER

This small glacier on the north side of Adolf Bay was fed from the same gathering-ground as the Nordenskiöld Glacier and also rested upon the pre-Devonian rocks. (See map, Fig. 12). The banded englacial material was well displayed in the sloping front of the ice forming the expanded foot of the glacier. By far the most interesting part of the glacier occurred in the upper part, where a well-marked "bottle-neck" compression of the glacier was to be seen (Fig. 13). Above this narrow neck the ice was heavily crevassed and contained abundant surface morainic material. Hummocky ice associated with thrust planes was also well developed. Fortunately, clear sections occurred at the nipped-in portion, showing the association of the ice with the underlying rocks. On the leeward side of a boss of rock, contorted ice filled with englacial material was extremely well shown and could be seen in three dimensions, associated with crevasses. The structure, which can best be appreciated from the photograph (Fig. 14), was somewhat analogous to the diagrams of

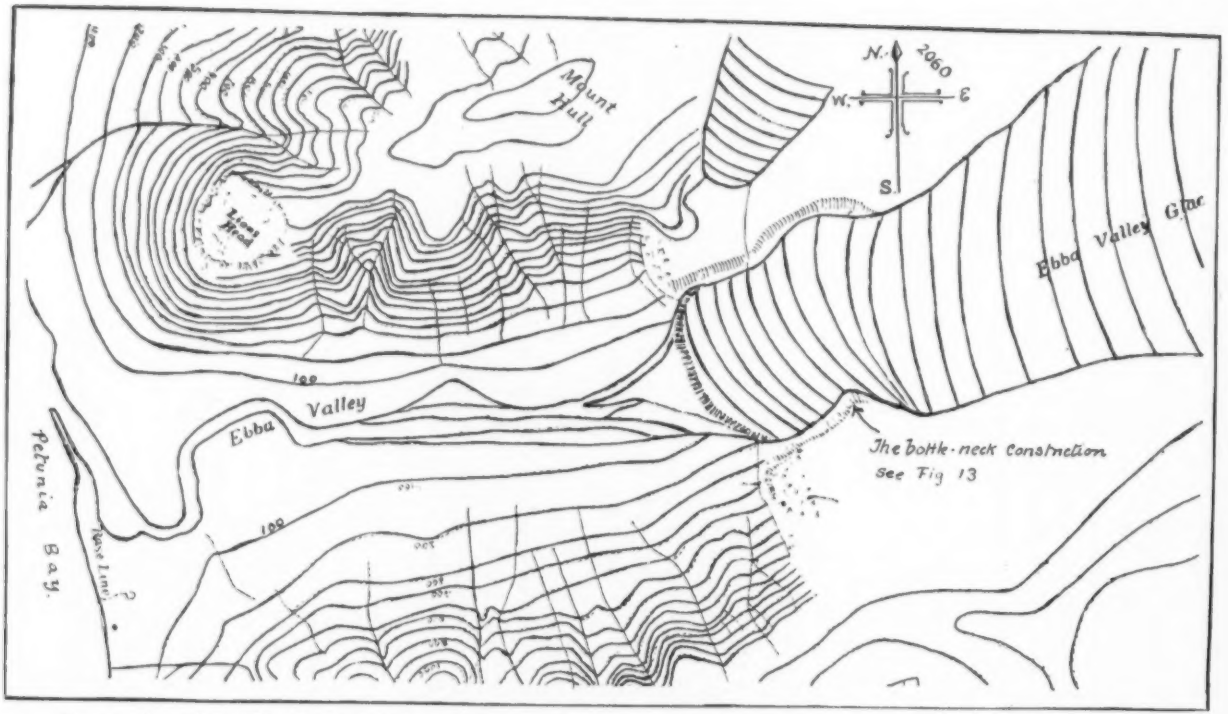



FIG. 12.—Map of the Ebba Glacier, Spitsbergen (Mathieson, 1919). Reproduced by permission of the Scottish Spitsbergen Syndicate, through the courtesy of J. Mathieson, Esq. Scale: 2 inches = 1 mile.

models of glacial action prepared and described by Professor Sollas.[1] Below the "neck" the ice fanned out and developed radiating crevasses. A single line of morainic matter occurred on the upper surface, and this was deflected sideward toward the precipitous southerly margin of the glacier at right angles to its termination. Here an interesting section was displayed, showing banded ice with lenticles

FIG. 13.—Ebba Glacier, showing the bottle-neck nip-in and expanded foot of the glacier.

of gravel and other englacial material curving upward. An outcrop of pre-Devonian rock near the front of the glacier appeared to be the cause of the inclination of the englacial bands. Owing to the rapid rate of ablation, the whole of the material in the ice was being melted out and converted into bands of gravel, sand, and mud.

### THE HÖRBYE AND SVEN GLACIERS

The Hörbye Glacier is situated west of Petunia Bay, the westernly termination of Klass Billen Bay, and adjoining Adolf Bay. The

[1] *Quarterly Journal Geological Society*, Vol. LI (1895), Part III, No. 203, pp. 361–68.

FIG. 12.—Map of the Ebba Glacier, Spitsbergen (Mathieson, 1919). Reproduced by permission of the Scottish Spitsbergen Syndicate, through the courtesy of J. Mathieson, Esq. Scale: 2 inches = 1 mile.

Sven Glacier is a tributary of the larger Hörbye Glacier; the latter was another example of a stagnant glacier having an expanded foot hemmed in by a crescendic moraine formed by the melting out of the well-marked bands of englacial material. The surface of the ice was smooth and rounded and covered by surface dust. When seen from a distance and under suitable atmospheric conditions, the sinuous lines of flow formed a striking spectacle. Near the junction between

FIG. 14.—Ebba Glacier. Contorted ice filled with englacial material on the leeward side of a boss of pre-Devonian rock, shown at the bottom right-hand side of photo. Line of surface moraine on left. (Photo by G. Slater.)

this glacier and the Sven Glacier was a deep glacial gorge or canyon with walls of pure greenish ice of homogeneous texture, and adjacent to this a surface moraine with a number of large ice cones covered with débris due to the rapid rate of melting of the ice.

### THE SVEN GLACIER

This glacier, although small, was extremely instructive, owing to the exceptional pressure of the névé ice, which passed downward over precipitous cliffs of Devonian rock, which was exposed in places. The pressure induced was localized; an amphitheatre of névé ice somewhat resembling a cirque showed an extreme development of thrust planes resembling imbricate structure (Fig. 15). From the

base of this cliff the surface of the glacier sloped downward to its termination, and at the foot of the cliff was a small crevasse. The structure of the ice forming the lower portion of the glacier was beautifully displayed along the vertical cliff, approximately 100 feet in height, forming the flank of the glacier. Here the lower zone of ice consisted of banded englacial material which rested upon the steep slope of the marginal moraine formed by the melting out of the englacial material and the shrinkage of the glacier. At the junction between the two was the usual glacial stream. The upper ice, forming

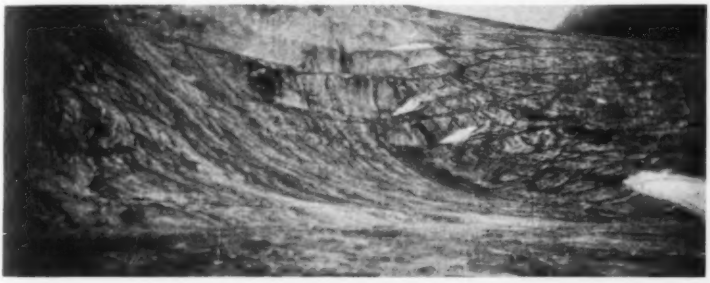
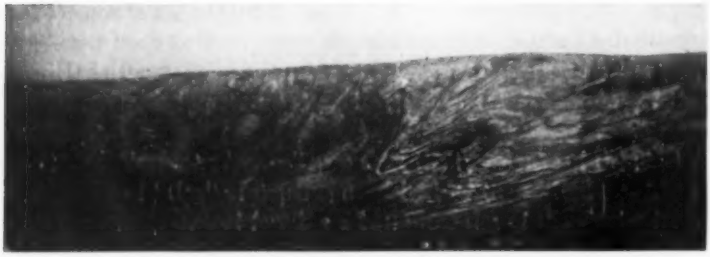


FIG. 15.—Sven Glacier. Névé ice full of thrust planes. (Photo by G. Slater.)

a cliff of considerable size, showed an entirely different structure and arrangement, and consisted of contorted ice associated with long, curved thrust planes, the curves sweeping gracefully from the top of the zone of dirt-filled ice below to the upper surface of the glacier. The upper surface of the zone of englacial material had acted as a glide plane over which the layers of névé ice had been carried by thrust planes (Fig. 16 A, B).

The presence of the vertical cliff suggested movement similar to that described in the southwestern section of the Nordenskiöld Glacier. In both cases a vertical cliff of ice occurred at right angles to the sloping stagnant termination of the glacier. The same thing also occurred in the Ebba Glacier. In the Nordenskiöld Glacier movement was proved in the case of the vertical cliff of ice, and this movement was irregular. In the Sven Glacier it was obvious that there had been differential movement of the various zones of thrust ice.

Now, on the surface of the Sven Glacier adjoining this section were a number of corrugations which curved toward the edge of the cliff, and were associated with a number of scattered sporadic heaps



A.—Sven Glacier. Contorted ice associated with curved thrust planes passing over lower ice filled with englacial débris. (Photo by G. Slater.)

B.—As in A. Closer view showing contortions and thrust planes. (Photo by G. Slater.)

FIG. 16

of surface morainic material (Fig. 17). The vertical section clearly showed that material was not being carried from below upward. This angular morainic surface débris was similar to the material in an arrested lateral moraine near the small crevasse already alluded

to. The sporadic heaps were isolated and linear in form, the longer axes being the same direction approximately as the cliff section, but

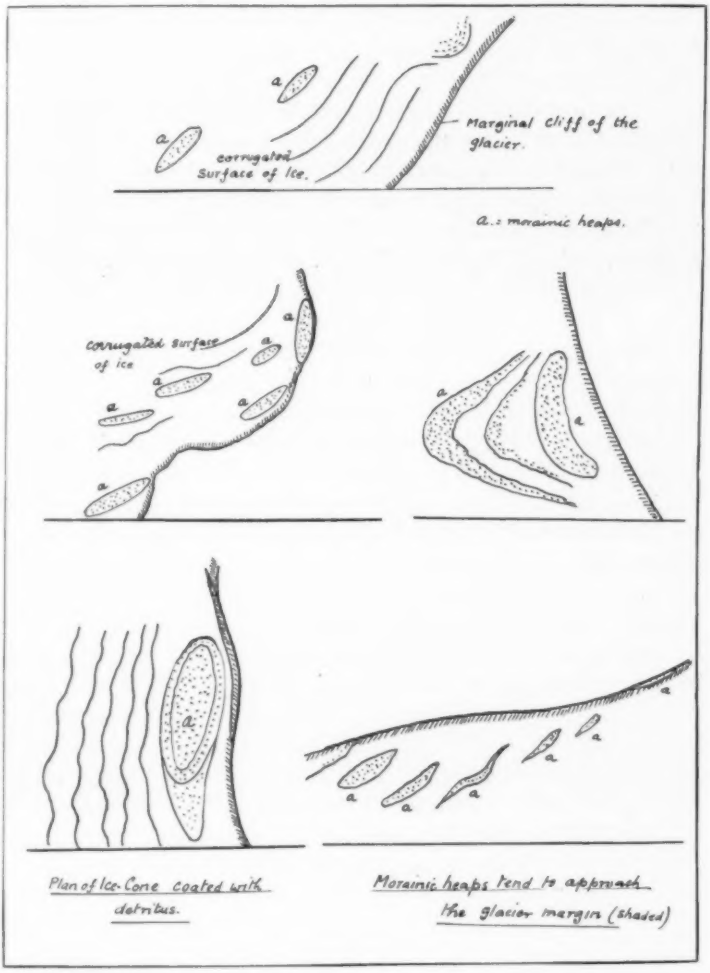

a
a
corrugated surface of ice.
Marginal cliff of the glacier.
a.: moraine heaps.
corrugated surface of ice
Plan of Ice-Cone coated with detritus.
Morainic heaps tend to approach the glacier margin (shaded)

FIG. 17.—Sven Glacier. Plan of ice surface. Sketches showing arrangement of morainic mounds.

curving toward it. (See sketches, Fig. 17.) The chief feature of these morainic heaps was that they were all laterally displaced from a general linear direction, and gradually approached the cliff edge as they were traced downward toward the termination of the glacier. They clearly point to differential movement toward the edge of the lateral cliff. Owing to obstruction at the termination of the glacier, movement had been arrested, leading to accumulation of the already abnormal pressure. This led to thrusting and contortion, and relief from pressure was obtained by differential movement toward the lateral cliff. The evidence of the Nordenskiöld Glacier also supports the view that a gradual accumulation of pressure is relieved at irregular intervals in a direction at right angles to the pressure.

## CONCLUSION

The expenses entailed in completing this investigation have been partly defrayed by a grant from the Royal Society of London, for which I express my sincere thanks.

To my friend Dr. J. Johnstone and to an anonymous donor I am indebted for contributions toward the cost of publication, while to Professor W. W. Watts I am indebted in many ways, but especially for his friendly criticism and advice during the preparation of the manuscript.

# PERMIAN AMPHIBIAN AND REPTILIAN REMAINS DESCRIBED AS *STEPHANOSPONDYLUS*

ALFRED SHERWOOD ROMER
University of Chicago

ABSTRACT

The remains assigned to the questionable cotylosaur *Stephanospondylus*, Stappenbeck, from the Rotliegende of Germany, are shown to belong partly to a typical diadectid reptile (the true *Stephanospondylus*) and partly to a rachitomous amphibian (*Onchiodon*). Some points concerning the Paleozoic reptilian fauna of Europe, especially *Solenodonsaurus*, are discussed.

## INTRODUCTION

In 1882 Geinitz and Deichmüller[1] described two series of slabs and counterslabs bearing vertebrate remains from the Middle Rotliegende of the Plauenschen Grunde, near Dresden. They believed these to represent two individuals of the same species, and because of the resemblance of certain of the vertebrae to those described by von Meyer[2] as *Phanerosaurus*, assigned the species to that genus, as *Phanerosaurus pugnax*.

In 1905 Stappenbeck[3] described these remains at length. He believed them to represent only one individual. Because of certain differences in the vertebrae he erected for them the new genus *Stephanospondylus*.

This form, as described and restored by Stappenbeck, has been a long-standing puzzle. In the vertebrae and teeth, it appears to be a diadectid reptile, to which group it is provisionally assigned by Watson,[4] and by Broili in Zittel's textbook. But, in many respects, especially in the girdles and limbs, it appears not only to be very unlike any diadectid, but indeed unlike any known Paleozoic reptile

[1] *Paleontographica*, Vol. XXXIX (1882), pp. 10–16.

[2] *Ibid.*, Vol. VII (1861), pp. 248–62.

[3] *Zeitschr. deutsch. geol. Ges.*, Vol. LVII (1905), pp. 380–437.

[4] *Proc. Zoöl. Soc.* (London, 1917), p. 171.

whatsoever.[1] An examination of Stappenbeck's figures leads one, as Williston has stated, to suspect inaccuracies in his work.

During a short stay in Dresden during the summer of 1923, I was given the privilege of examining this material. It soon became apparent that two individuals were present. Further studies have shown that one of these is a rachitomous amphibian, while the other is a very normal diadectid reptile; that in consequence of his assumption as to the unity of the material, Stappenbeck had wrongly interpreted it; and that a revision was badly needed.

Since time was lacking for a thorough study of the remains on the spot, a series of squeezes of the slabs was made and shipped to this country; the description below is prepared from them. The bone had been removed from the slabs by Steppenbeck, leaving impressions from which sharp positives may be obtained, frequently of both sides of the bone. However, due to inability to compare the squeezes with the originals during the course of the study, and further, to some slight damage incurred by the squeezes in shipment, it is possible that some errors, in the main those of omission, may be found.

I wish to express my warm appreciation of the many courtesies shown me while in Dresden by the authorities of the Mineralogical and Geological Institute, and especially of the material assistance rendered me by Dr. K. Wanderer. I also wish to thank Mr. J. H. Taylor, of the Royal College of Science of London, for his aid and for furnishing me with photographs of the specimens.

## DESCRIPTION—SPECIMEN I

This, the smaller of the two, is, it may be stated in advance, the true cotylosaur *Stephanospondylus*. The remains are found strewn over two slabs and their counterparts, whose relations are diagramed in Figure 1 for the convenience of future workers. Geinitz and Deichmüller figured a portion of slab *Ib2* in Plate IV, Figure 1, and other bones from this specimen in Figures 2–8 of the same plate. The originals of at least the following of Stappenbeck's figures are found here: 1–3, 8–14, 19 (*partim*), 21, 23, 24, 30 (*a*, *c*, *f*), 31.

*Vertebral column.*—A large proportion of the remains of this specimen consists of vertebrae; I have counted at least seventeen

[1] S. W. Williston, *Jour. Morph.*, Vol. XXIII (1912), p. 562.

of them on this set of slabs. A majority of them have been figured by Stappenbeck, his Figures 11 and 12 being from slab *Ib2*, and Figure 13 from *Ib1*. He has described them sufficiently well to establish their typical cotylosaurian and apparently diadectid character, with very broad and massive neural arches, and zygapophyses placed wide apart. As he states, hyposphene-hypantrum articulations are not observed. I believe, by comparison with typical diadectids, that his interpretation of the regions from which the vertebrae are derived is, in the main, incorrect. His *Rumpfwirbeln* (Figures 11*b*, 12*a* and *b*, 13, 14) are apparently from the anterior end

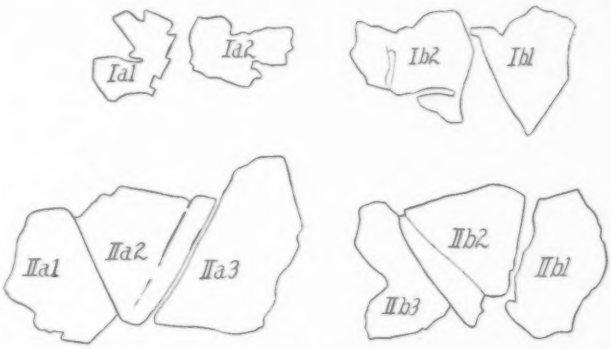



FIG. 1.—Reduced diagrams of the slabs constituting the two specimens: smaller (No. I) above; larger (No. II) below.

of the column, with the characteristic reduction of the spines in this region. His 11*c*, *Halswirbel*, is probably one of the last presacrals. His Figure 10, *Halswirbel*, which is apparently a composite, seems to be a proximal caudal. His sacral ribs, and apparently his caudals as well, are derived from Specimen II; there are, however, a number of caudal vertebrae present in this specimen, especially on *Ib1*.

*Ribs.*—Long, slender ribs from the middorsal region appear in a number of places on the slabs; two are figured by Stappenbeck (30*b*, *c*); another may be seen near the bottom of Geinitz and Deichmüller's Plate IV, Figure 1. There are also a number of expanded ribs seen especially well on *Ib1*. Three are figured by Stappenbeck, one (Fig. 3) as a quadrate, and two as sacral ribs (Fig. 31). These are comparable with the broad ribs found in the subscapular region

of many primitive tetrapods, and approach in the degree of expansion those of *Diadectes*, although they are not so pronounced in the development of a posterior "hook" as is the case in that form. My interpretation of their nature and position is strengthened by the fact that they are found in the specimen associated with the two scapulae and humeri. The two figured as "sacral ribs" show a slight distinction between tuberculum and capitulum. The supposed quadrate has its true character slightly obscured by the fact that its proximal end lies on a crack in the matrix and the distal end has been somewhat crushed over on itself.

The presence of broad ribs in the scapular region has been cited by early workers, and even by Nopsca,[1] as indicating the development of a turtle-like protective armor. But it will be noted that these ribs are for the most part located beneath the scapula where, of all places, they would be of the least possible use. Strong ribs are found in this region in forms as far apart as the amphibian *Eryops* and the dicynodonts.[2] I have previously[3] pointed out their function as points of origin for the strong serratus anterior-levator scapulae series of muscles which hold the body in a sling from the scapulae.

*Skull.*—A number of fragments of the skull are present on *Ia2* and the reverse, *Ib2*. The parietal-frontal region, and the squamosal, as figured by Geinitz and Deichmüller (Plate IV, Figs. 1 and 4) and used by Stappenbeck in his restoration of the skull (Plate XIX), are found on *Ib2*. The inner surface of the parietal and frontals are on *Ia2*, with the outline of the large pineal shown, as well as prominent curved ridges on the lateral border of the frontals (noted by Stappenbeck). The breadth of the parietal is comparable with the diadectid condition. Of the other bones figured by Stappenbeck in his figure of the skull roof, most are doubtful fragments; his "jugal" and "lacrimal," at least, are from Specimen II. His basisphenoid (and parasphenoid) (*Ib1*) is correctly identified. The reverse of this fragment (*Ia1*) appears to show the two lateral walls of the "sphenethmoid" and the sella turcica. I have not found on my material the originals of his prevomers or questionable epipterygoid. His

[1] *Fortschritte d. Geol. u. Pal.*, Vol. II (1923), p. 40.

[2] H. S. Pearson, *Proc. Zoöl. Soc.* (London, 1924), p. 837

[3] *Bull. Amer. Mus. Nat. Hist.*, Vol. XLVI (1922), Plate XXVIII, etc.

palatine is the outer surface of the left dentary (on *Ia2*). The large element figured by Geinitz and Deichmüller (Plate IV, Fig. 1) as "pterygoid" is poorly represented on my squeezes; and there are several other fragments, of the nature of which I am not certain.

Instead of fragmentary portions of the tooth rows, as believed by Stappenbeck, the pieces represented in Specimen I comprise the greater part of a typical diadectid dentition. (His "mandibles" belong to Specimen II.) The "fragmentary right premaxilla and maxilla" of Stappenbeck (his Fig. 2) (Plate *Ib1*) is an internal view of the left mandible of a normal diadectid. The dentition, as preserved, consists, posteriorly, of a row of nine teeth, tranversely elongate; then a break, where the slab is incomplete; in front, three large "incisors." This figure (inverted, of course) will stand close comparison with that of any typical American diadectid, such as that of *Diadectes lentus* given by Case and Williston.[1] Here there are also nine teeth in a similar series posteriorly; anteriorly, there are four incisors and two teeth of intermediate character. Since the jaw under consideration is obviously imperfect near the anterior end, it is possible that there were the same number of teeth in both cases. Due to crushing, the detailed structure of the jaw cannot be made out; it was obviously deep and heavy as in American diadectids. Stappenbeck calls attention to the alveoli found on the inner surface of this jaw. They have long been known in diadectids, and are shown in the figure of Case and Williston referred to. However, this does not mean, as Stappenbeck states (and used as a diagnostic character) that two rows of teeth were present.

A series of seven teeth, of which an excellent figure is given by Geinitz and Deichmüller (Plate IV, Fig. 3) is found on *Ib2*. These are quite comparable with the teeth mentioned above, and constitute the posterior part of the right mandibular dentition. Alveoli are seen here, as well, internal to the teeth. Close beside is a fragment of the anterior part of the jaw, with two of the incisors. The articular region of the jaw is also preserved.

On slabs *Ia2* and *Ib2* is a series of twelve teeth, which are figured by Geinitz and Deichmüller (Plate IV, fig. 2). From their figure, it will be seen that this is an outer view of the right maxilla, compar-

[1] *Amer. Jour. Sci.*, Vol. XXXIII (1912), p. 344.

able with that of an ordinary diadectid. A tiny tooth at the posterior end is succeeded by nine transversely elongated, and then by two of more conical form. In the maxilla of *Diadectes lentus*, as figured by Case and Williston, there are nine posterior transversely elongated teeth, followed by two which are more rounded. The only obvious difference is the presence of a very small additional posterior tooth in this specimen.

The remainder of the upper dentition is not preserved.

The details of the teeth are not too well shown on my squeezes. In the molar teeth, there appear to be a central cusp, but no lateral

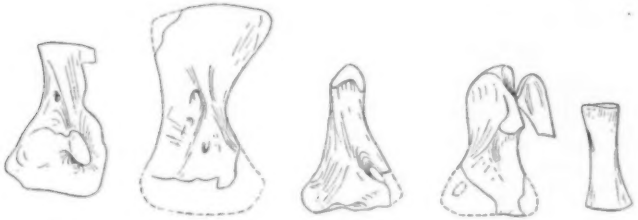



FIG. 2—Specimen I (*Stephanospondylus*) (×¾): (*a*) right scapulo-coracoid, external; (*b*) left scapulo-coracoid, internal; (*c*) left humerus, distal dorsal surface; (*d*) left humerus, distal ventral surface, and head of ulna; (*e*) radius.

ones, thus perhaps resembling Case's *Desmatodon*.[1] Stappenbeck believed the grooved roots to be distinctive; they have long been known in *American* diadectids.[2]

*Pectoral girdle.*—Stappenbeck's girdle (Fig. 2) is a composite of parts from both specimens.

The true right scapulocoracoid is well shown, the external surface on *Ib1*, the internal on *Ia1*. Stappenbeck considered this the left coracoid, and has shown its two surfaces in his figures 19 and 21, respectively. If the former figure be reversed, it will be seen that it is of a typical primitive tetrapod form, showing a characteristic screw-shaped glenoid, and supraglenoid buttress, with the supraglenoid foramen. The internal view shows the depression from which

[1] *Ann. Carnegie Mus.*, Vol. IV (1908), p. 236.

[2] Case, *Pub. Carneg. Inst. Wash.*, No. 145 (1911), p. 70.

the supraglenoid and coracoid foramina originate, and also shows, more posteriorly, the internal opening of the primitive glenoid foramen. The scapulocoracoid of the left side is obscured by ribs and other elements on both aspects; it lies not far from the right. Its general outline can be made out, but little structure is visible other than the prominent anterior and posterior glenoid bases of the supraglenoid buttress. I have been unable to identify, surely, elements of the dermal girdle, other than one cleithrum at the far end of *Ib2*. This is narrow, but distinctly of the "capping" type of *Diadectes*.

*Pectoral limb.*—Stappenbeck (Fig. 2) has correctly identified the humeri, which are both present (*Ia1* and *Ib1*), but he has reversed their ends and curiously misinterpreted them. The true entepicondyle is his "tuberculum minus," the ectepicondyle his "capitulum," the supinator process his "tuberculum major." I find nothing to represent the structure which he takes to be an incomplete entepicondylar foramen. The foramen was, nevertheless, present, and is well exhibited on the left humerus, although this is somewhat imperfect. The humerus is of a primitive reptilian character.

The head of the right ulna is present near the right humerus. One radius is found on *Ia1* and *Ib1*, and part of the other on *Ib2*, near the cleithrum. Of the feet I can identify nothing, except one or two stubby phalanges.

*Pelvic girdle and extremity.*—These are not represented in the specimen.

### DESCRIPTION—SPECIMEN II

As was the case with Specimen I, the remains are strewn with no apparent order over a series of slabs and counterslabs, a key to the arrangement of which is given in Figure 1. Geinitz and Deichmüller have figured part of slab *IIa2* in Plate *IV*, Figure 10, and part of *IIa1* in Plate V. Their Figure 9, Plate IV, and Stappenbeck's Figures 8, 9, 15, 16, 17, 18, 19 (*partim*), 20, 22, 25–29, and 30 (*partim*) are also from this specimen.

*Vertebrae.*—The large vertebrae (Fig. 3) with heavy neural arches so characteristic of Specimen I are not to be found here. Instead, separate neural arches and central elements are present. The neural arches are obviously rachitomous. Stappenbeck's "sac-

ral" vertebra (his Fig. 15) is from this specimen. A number of intercentra, of rachitomous shape, are scattered about the slabs; I have figured a few of them. Other elements, smaller and less regular in apparent outline, I take to be pleurocentra. In one case, near the femur on *IIb1*, two pairs of small bones are surely to be placed in this category. On *IIa3* near the right femur, haemal arches are indicated.

Apparently Stappenbeck considered the vertebrae from this specimen to be mainly postsacral, and used them to form the long tail in his restoration. I fail, however, to find the originals of his restored caudal vertebrae (his Fig. 16).

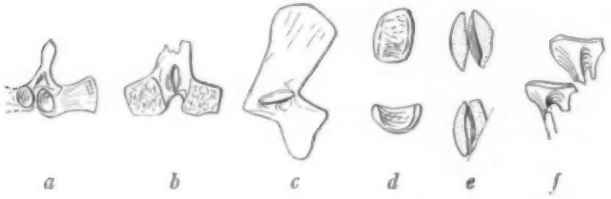



FIG. 3.—Specimen II (*Onchiodon*) $\times\frac{1}{2}$): (*a*, *b*, *c*) anterior, posterior, and lateral views of imperfect neural arches; (*d*) intercentra; (*e*) pleurocentra; (*f*) haemal arches.

*Ribs.*—These are not numerous. Stappenbeck has figured ribs from this specimen (slab *IIa1*) in his Figure 30*b*,*d*,*e*.

*Skull.*—Numerous fragments, many showing sculpturing, are found, especially on *IIa2* and *IIb2*. Some of these were used by Stappenbeck in making his composite skull. Restoration is impossible. Two large fragments of jaws from *IIa2* are figured by Geinitz and Deichmüller (Plate IV, Fig. 10) and Stappenbeck (Fig. 4). They consist of the dental surfaces with the teeth missing, but showing the alveoli. Stappenbeck considered them the mandibles; they are more probably maxillae. The fragments are characteristically "labyrinthodont" comparable, for instance, with the jaw figured by Credner from the same locality as *Sclerocephalus*.[1] These fragments cannot be reconciled with the type of dentition found in Specimen I.

[1] *Zeitschr. deutsch. geol. Ges.*, Vol. XLV (1893), Plate XXX.

A fragmentary lower jaw is found on *IIa1* and *IIb1*. A portion of the outer sculptured surface is visible, as are a few alveoli.

Other parts of the skull include Stappenbeck's "jugal," which is perhaps a fragment of the pterygoid, and what is perhaps a portion of the parasphenoid.

*Shoulder girdle.*—The right scapulo-coracoid (Fig. 4) is preserved on *IIa1*. While the general shape is shown, little detail is preserved except for the prominent anterior angle of the glenoid. The reverse, *IIb1*, shows only the interior of the supraglenoid region. This bone was figured by Stappenbeck as the left ischium. The posterior half

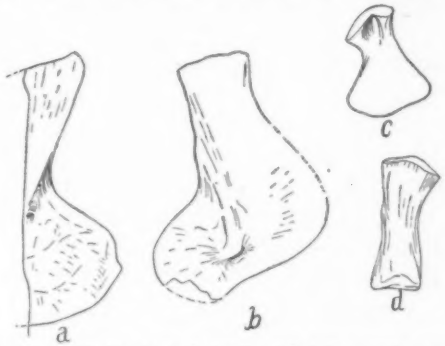



FIG. 4.—Specimen II (*Onchiodon*) (×½): (*a*) left scapulo-coracoid; (*b*) right scapulo-coracoid; (*c*) incomplete humerus; (*d*) radius.

of the left scapulo-coracoid is shown on *IIa3*. The reverse of this is not preserved. This was described by Stappenbeck as the left scapula (an ischium and another complete primary shoulder girdle from Specimen I being added as "procoracoid" and "coracoid").

One clavicle and the interclavicle have been figured by Geinitz and Deichmüller (Plate IV, Fig. 10) and Stappenbeck (Figs. 17, 18). Stappenbeck has correctly identified one cleithrum from slab *IIa2* (his Fig. 20), while the other is to be found in another part of the same block. They have an expanded upper end and a long shaft, much as in Eryops. What appear to be the upper ends of both clavicles are found on *IIa3* and the reverse on *IIb3*.

*Pectoral limb.*—What I take to be the right humerous (Fig. 4), with the proximal portion missing, and the distal end not well ossi-

fied, is found on *IIa2*. This was described by Stappenbeck as the ulna. The right, radius, nearby, was identified by Stappenbeck as such. The distal end of the left is shown on another part of the same slab. A bone which may be the distal end of an ulna, but concerning which I have considerable doubt, is present on slab and counter-slab 3.

Stappenbeck's restoration of the carpus, from this specimen (his Fig. 26) is erroneous. A number, at least of the scattered bones, on

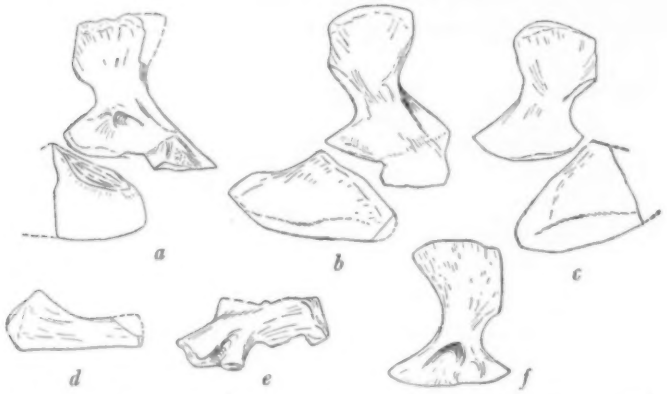



FIG. 5.—Specimen II (*Onchiodon*) (×½): (*a*) right pelvic girdle, exterior; (*b*) left pelvic girdle, interior; (*c*) right pelvic girdle, interior; (*d*) fibula; (*e*) femur; (*f*) left ilium, external.

*IIa2*, from which his reconstruction was made, are intercentra and pleurocentra. Many scattered metapodials and phalanges are to be found, especially on *IIa2*, several of which are figured by Stappenbeck (his Fig. 27). I doubt the existence of clawed end phalanges.

*Pelvic girdle.*—From both sides of the body ilia (Fig. 5) ischia and fragments of the pubis are preserved. The ilia are typically rachitomous, lacking the posterior extensions of various sorts found in the *Embolomeri* and reptiles. The protuberance found on the lower posterior border of the right ilium, on *IIa1*, *IIb1* and figured by Stappenbeck as part of that bone (his Fig. 22) is an accidentally associated intercentrum. Attached to the inner side of the left ilium and the outer side of the right, small portions of an ossified pubis may

be seen, the latter showing the characterisrtic rough point of attachment for the ambiens and pubo-tibialis muscles. I am not sure whether the absence of the remainder of these bones is altogether due to the accidents of preservation; they were perhaps poorly ossified. Both ischia are preserved, although both are somewhat incomplete, the right on *IIa2* and *IIb2*, the left on *IIa3* and *IIb3*. Both show a well marked symphysis; the right shows the acetabular margin. One of these was used by Stappenbeck as a "procoracoid."

Stappenbeck's restoration of the left pelvic girdle consists of the right ilium, the right scapulocoracoid as the ischium and what is apparently a sacral rib, found close beside the left ilium, functioning as the pubis.

*Pelvic limb.*—Both femora are present, not far from their respective ilia, the right on *IIa3* and *IIb3*, the left on *IIa2* and *IIb2*. Both are crushed and distorted. One, the left, has been correctly identified by Stappenbeck (Fig. 29). The dorsal surface of the right, as preserved, is shown in Figure 5.

An uncrushed thin bone which I agree with Stappenbeck in calling the right fibula is shown on *IIa2* and *IIb2*. Apparently no tibia is preserved; from Stappenbeck's description, the bone which he considered to be that element is a cleithrum; I fail to find the original of his figure.

## DISCUSSION

*Analysis of material.*—The description has, I think, made it clear that the remains are those of two individuals, not one, as Stappenbeck supposed. Such facts as the presence of four shoulder girdles cannot be reconciled with his conclusion.

Further, the two individuals are not of the same type. This is evident from a comparison of the homologous elements. The vertebrae of Specimen II are rachitomous; those of Specimen I, diadectid. The differentiated dentition of Specimen I cannot be reconciled with the even tooth-rows of Specimen II.

*Specimen II—"Onchiodon."*—As seen from the foregoing description, this animal is a rachitomous amphibian, probably one of the genera known from the same locality. It is certainly not *Archegosaurus*, as the shape of the ilium and the ossification of the pubis

show, nor the small and peculiar *Discosaurus*. The comparatively unexpanded dermal shoulder girdle distinguishes it from the true *Sclerocephalus*. It agrees perfectly, as far as known, with the remains of *Sclerocephalus* described by Credner,[1] for which Watson[2] has revived the term *Onchiodon*, and adds considerably to our knowledge of the postcranial anatomy of that form.

*Specimen I—Stephenospondylus.*—This, when purged of the amphibian characters and duplicated elements caused by Stappenbeck's erroneous understanding of the situation, emerges as a typical diadectid, differing markedly in no known character from the well-known American forms, although a more complete knowledge of the animal might show differences to be present.

Geinitz and Deichmüller described *Stephanospondylus* (*Phanerosaurus*) *pugnax* from both sets of plates. However, the main character upon which they placed emphasis was the presence of the diadectid vertebrae which they saw to be of the same type as those upon which the genus *Phanerosaurus* was founded. These are found in the *Kleineren Individuum*, Specimen I, and the name should be thus applied to the diadectid and not the amphibian.

Stappenbeck (p. 426) lists seven characters in which the vertebrae of *Stephanospondylus* differ from those of *Phanerosaurus*, on the strength of which he established the former genus for *P. pugnax*. His first point of distinction is that the centra of *Phanerosaurus* are suturally separated from the arches, while the two elements are fused in *Stephanospondylus*. But we do not know the condition of the anterior part of the column of *Phanerosaurus;* the *Stephanospondylus* vertebrae are all seen in end view, and we cannot be sure of the absence of lateral sutures in most cases; and, further, this may be an age difference, as we know it to be in many primitive forms. His second and third points are trivial; the remainder are based upon his erroneous beliefs as to the constitution of the sacral region in *Stephanospondylus*. Hence there is little reason for separating the two. However, *Phanerosaurus* may turn out to be a distinct, although closely related, form if more remains should ever be dis-

[1] *Zeitschr. deutsch. geol. Ges.*, Vol. XLV (1893), pp. 639–706.

[2] *Phil. Trans. Roy. Soc. London* (B), Vol. CCIX (1919), p. 4.

covered; and the genus *Stephanospondylus* may be allowed to stand for the present.

Stappenbeck gives a lengthy diagnosis of the genus. Of the features listed, many are derived from Specimen II and consequently have no application; many are founded upon erroneous interpretation of the material; the remainder are characters common to all diadectids. *Stephanospondylus* is thus undefined; and a definition is difficult. It may be characterized as a small diadectid, probably about 1 meter in length, lacking a hyposphene-hypantrum articulation; the subscapular ribs, although very broad, lack the V-shaped posterior angles found in *Diadectes;* the molar teeth lack lateral cusps. Fuller knowledge might allow a fuller characterization; and it is probable that a thorough search through the material from the Rotliegende would reveal other fragmentary specimens of this diadectid.

The exact size of the animal cannot, of course, be determined. But since the known parts are of similar structure and shape to those of American diadectids, a rough idea of the complete measurements may be obtained. If the length of the tooth-rows of the lower jaws are compared with those of described American forms, it will be found that the lower jaw was in the neighborhood of 160 millimeters in length. Again, a comparison of the maxillary teeth and the parieto-frontal region gives a skull length (to the occipit) of about 155 millimeters.—Since the jaw articulation in diadectids is usually somewhat posterior to the occipit, these measurements agree. Again, the limb bones and vertebrae may be compared with those of *Diadectes phaseolinus*, as described by Case,[1] which is the best known of diadectid skeletons. From an average of the possible measurements, it will be seen that *Stephanospondylus* is roughly three-fifths the size of this skeleton, and thus the length of the body to the sacrum may be estimated with a fair degree of accuracy as 65 centimeters, and to the tip of the tail, at approximately 1 meter. The skull of *Stephanospondylus* is somewhat larger in proportion, as might well be the case in a small animal.

As may be inferred from details mentioned in the description,

[1] *Pub. Carneg. Inst. Wash.* No. 145 (1911), Plate XIV, etc.

Stappenbeck's restoration is incorrect in almost every particular. If a restoration of *Stephanospondylus* be needed, one of *Diadectes* will answer the purpose in a more satisfactory manner.

*Permian vertebrate faunas*—The position of *Stephanospondylus*, as redescribed above, may be examined in its relations to other European Paleozoic cotylosaurs. In the Paleozoic fauna, as considered here, the upper Permian, with its apparent intrusions of the South African types of reptiles, will not be considered. These forms are really more Triassic in character. Indeed, in regard to vertebrates, the Permian period might better be defined as including the uppermost Pennsylvanian and Lower Permian, opening with the appearance of the *Rachitomi*, *Cotylosauria*, and *Pelycosauria* (Pittsburgh shale, Nurschan in Bohemia). The appearance of the pareiasaurs, typical therapsids, and thecodont diapsids (in South Africa) in the upper part of the Permian ushers in the Triassic vertebrate life.

The lower boundary of this suggested faunal division agrees better with the diastrophic evidence than the usual Pennsylvanian-Permian boundary. Case has repeatedly demonstrated the existence of Permo-Carboniferous conditions in this continent; the vertebrates which Fritsch and others have described from Bohemia indicate the continuity and similarity of the Upper Pennsylvanian and basal Permian faunas of that region.

At the upper boundary, it is well known that the plants (as well as the vertebrates) of the European Upper Permian (Zechstein) are distinctly Mesozoic in character.

In the typical Paleozoic of Europe, as limited above, cotylosaurs are extremely rare.

"*Phanerosaurus*."—Discussed above; known only from a few diadectid vertebrae from the Middle Rotliegenden.

Thevenin[1] also assigns to the *Cotylosauria* a fragment of skeleton from the Lower Permian of Belmont, France. This may well be diadectid, but cannot positively be identified from his description. Dr. E. C. Case informs me that he saw in the Sorbonne two typical diadectid vertebrae from an unknown, probably Lower Permian, locality in Auvergne.

[1] *Ann. de Pal.*, Vol. V (1910), pp. 1–64.

The foregoing, with *Stephanospondylus*, constitute all known diadectid remains from Europe.

"*Sauravus*," "*Eosauravus*."—The former is described by Thevenin[1] as a reptile from the Lower Permian of France. After examination of the specimens, I find no reason to disagree with Watson[2] in placing the genus in the "lepospondylus" amphibia. *Eosauravus*, from the famous Linton coal mine of Ohio, has been ranged by Williston[3] with the last mentioned as members of a group of ancestral reptiles. But the anterior half of the single specimen is missing, and all conclusions must be based upon the vertebral column and limb. In the former region, the presence of broad neural arches and the possible presence of two sacrals are pointed out as showing reptilian affinities. But the specimen is none too clear in this region; further, the presence of two sacral ribs is not a distinctly reptilian character, as Williston himself later showed. On the other hand, the absence of intercentra, retained in a great number of much later reptiles, points to the *Lepospondylia*.

The presence of a reptilian formula in the foot phalanges is in contrast with what is known of amphibian feet. But we know practically nothing of the phalangeal formula in the *Embolomeri* and very little of that of the *Lepospondylia*. This formula may mean merely the retention of a primitive amphibian one. On the other hand, the absence of the tibiale in the foot is in contrast with its persistence in the much later *Seymouria*.

All in all, the claims of *Eosauravus* to reptilian position are slight. It may better be placed as *incertae sedis* in the (undoubtedly composite) *Lepospondylia*, with a number of other ill-known forms. It has no place in a conception of reptilian ancestry such as that suggested by Watson's comparison[4] of *Seymouria* and the *Embolomeri*.

"*Gephyrostegus*."—As suggested by Broili,[5] this skull from the Upper Pennsylvanian of Nurschan may well be reptilian. The same

[1] *Op. cit.* and *Ann. de Pal.*, Vol. I (1906), pp. 145–63.

[2] *Proc. Zool. Soc.*, (London, 1918), p. 293.

[3] *Jour. Geol.*, Vol. XVI (1908), pp. 175–92.

[4] *Proc, Zoöl. Soc.* (London, 1918), pp. 267–301.

[5] *Sitz. Bayer. Ak., d. Wiss. Math.-Nat. Abt.* (1924), pp. 3–11.

shape of skull, however, may be found in the *Embolomeri*, and no figures other than that of the skull roof are given by Jaekel.[1]

"*Solenodonsaurus*."—This genus, described by Broili[2] from the Upper Pennsylvanian of Nurschan, is of great interest. If *Eosauravus* be left out of consideration, only the fragmentary diadectid jaw described by Case from the Upper Pennsylvanian of America can be ascribed to an earlier date. It is a cotylosaur and, from the possession of an amphibian type of otic notch, a very primitive as well as a very early one, although somewhat advanced in a few features, such as considerable reduction of the intercentra and a lack of distinctness of capitulum and tuberculum. Miss Pearson,[3] in describing a second specimen, also emphasizes its primitive position, and places it in Watson's group of *Seymouriamorpha*. With her conclusions I must, however, differ in one respect. It is stated that the neural arches are broad, the zygapophyses widely separated. From her description of the fragmentary neural arches present in the D. M. S. Watson specimen, I cannot believe that the point can be proved from this material; there is nothing in Broili's description to to substantiate it; and, as I remember the Berlin original, the most characteristic feature of the specimen was the narrowness of the neural arches.[4]

The embolomerous ancestors of the reptiles, so far as I am familiar with them, have narrow neural arches; *Pantylus* among the cotylosaurs has narrow neural arches; so have the *Proterosauria*, *Araeoscelis*, the pelycosaurs (with a very slight exception in the case of *Poecilospondylus*), and most later groups of reptiles. With these, *Solenodonsaurus* is in agreement. On the other hand, *Seymouria*, diadectids (such as *Stephanospondylus*), the *Captorhinomorpha* and indeed all other cotylosaurs (except *Pantylus*), and the *Mesosauria* as well, have very broad and heavy nueral arches. The reasons for the interpolation of heavy-arched forms in a series leading from amphibians to non-cotylosaurian reptiles are not obvious. Heavy arches can hardly be a locomotor adaptation; many of the primitive pely-

[1] *Jahrb. deutsch. geol. Ges.*, Vol. LIV (1902), pp. 127–32. [2] *Op. cit.*

[3] *Ann. Mag. Nat. Hist.* (9), Vol. XIV (1924), pp. 338–43.

[4] Since the above was written, Dr. Broili writes: "Obwohl die oberen Bogen bei *Solenodonsaurus* durch Druck deformiert sind, so sind sie doch nicht breit gewesen, sondern schmal."

cosaurs are more clumsy and more heavily built than typical captorhinomorphs. It seems much more reasonable to assume that the light arches of *Solenodonsaurus* are a truly primitive reptilian character; that *Seymouria* represents a departure, although a very slight one, from a primitive light-arched form toward the typical cotylosaurs, which are a self-contained group (except perhaps for *Mesosaurus*); and that *Solenodonsaurus* represents a departure from this primitive form in the direction of *Pantylus*, the *Proterosauria*, the pelycosaurs, and all later types.

If the term *Seymouriamorpha* be used to include primitive cotylosaurs of any character, *Solenodonsaurus* may be included in the group; but if, on the other hand, a vertical rather than a horizontal system of classification should be attempted, *Solenodonsaurus* should be placed with *Pantylus* in Case's group *Pantylosauria*.

It is, of course, unwise to lay too great stress upon any one character in attempting to work out phylogenies. But the discussion above does, I think, tend to emphasize the present inadequacy of our knowledge of very early reptiles and the connecting links between them and most of the later orders.

*Solenodonsaurus* was originally described as a specimen of the amphibian *Cochleosaurus*, possessing an entepicondylar foramen.[1] Its recognition as a reptile now leaves *Diplocaulus* as the only amphibian in which this structure is known to exist.[2]

The forms discussed comprise all know cotylosaurian remains from the European Paleozoic, as restricted above. One diadectid, one very primitive cotylosaur, neither well known, and a few fragments of vertebral columns represent the entire fauna, as contrasted with the long series of forms which are listed from the Permo-Carboniferous of America. Pelycosaurian remains are equally scanty. On the other hand, amphibian remains (some of them closely allied to American types) are numerous. It is probable that the differences between the Rotliegende and the American "Red Beds" lie merely in the fact that the latter are more terrestrial in their nature and that the faunas of the two regions in Permian times were of a similar character.

[1] Broili, *Paleontographica*, Vol. LII (1905), pp. 1–16.

[2] *Romer, Bull. Amer. Mus. Nat. Hist.*, Vol. XLVI (1922), p. 557.

# A PROBABLE FOSSIL GLACIER

W. HORATIO BROWN
Denver, Colorado

ABSTRACT

Mining operations in Hurricane Basin, in the Silverton Quadrangle of Colorado, have disclosed the presence of a body of ice beneath rock-stream and landslide débris. The ice is believed to represent the remnant of a glacier, and the relations appear to confirm the suggestion of Cross and Howe that the rock débris buried small glaciers remaining in the cirques after the ice disappeared from the main valleys.

The rock streams of the Silverton Quadrangle, Colorado, were first described by Cross and Howe.[1] In a later paper Howe[2] summarized the opinion which they had formerly held concerning the origin of the rock streams in the following sentence: "The débris was supposed to have been supplied as a result of landslides to the surfaces of small glaciers which lingered on in the cirques some time after the retreat of the ice in the main valleys." Howe then went on to show that this was not the only way in which rock streams formed, and gave other possible methods. His paper was illustrated with many pictures of San Juan cases, including the one discussed below.

According to the miners in the San Juan region, it is not uncommon to find slide rock in the high basins cemented by ice. During recent development work by the Golconda Mines Consolidated, in Hurricane Basin, a variation from the ordinary icebound talus slope was found. A cross-cut was started at the lower end of the area mapped as landslide by the United States Geological Survey, to cut the large vein crossing the basin. The work was started at this point in order to keep out of the path of snowslides.

The surface overlying the tunnel appears to be a combination of landslide and rock-stream topography. The front of the pile of débris is steep. The top is billowy, and some of the depressions are

[1] Whitman Cross and Ernest Howe, *U.S. Geol. Survey Atlas, Silverton Folio* (No. 120), 1905.

[2] Ernest Howe, "Landslides in the San Juan Mountains, Colorado," *U.S. Geol. Survey Prof. Paper 67* (1909), p. 49.

deep enough to suggest the depressions in the top of a landslide area. Some small ponds of water are found in these depressions, but they are not very permanent.

The tunnel was started in, and for the first few feet penetrated typical rock-stream débris consisting of angular blocks. For the next three hundred feet the material was cemented by ice, but the quantity of rock in the ice varied, as did the size of the angular blocks of rock. After penetrating this material, the tunnel was

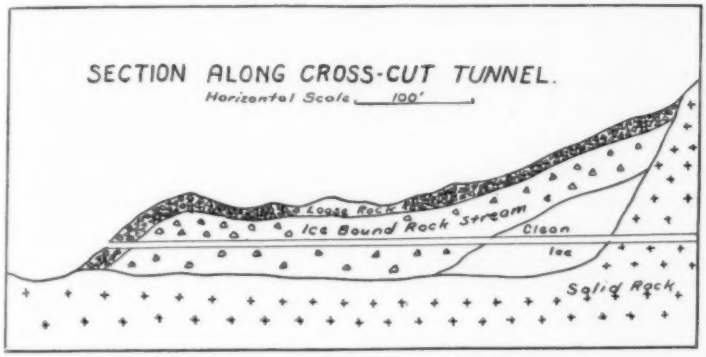



FIG. 1

driven for one hundred feet through very clean ice before reaching solid rock. The relations of the various kinds of material can be seen from Figure 1.

Howe gave a diagram[1] which was intended to illustrate the mechanics of rock-stream formation. If the section above (Fig. 1) is compared with that given by him, the similarity is striking. Figure 1 shows the process as outlined by Cross and Howe entirely completed. This has convinced the writer that some rock streams, the one described here in particular, are certainly formed as Cross and Howe suggested. That this, however, is not the only method of rock-stream formation has been clearly shown by other investigators.

It is believed that the ice encountered in the tunnel is glacial ice, but one must consider the possibility that this supposed glacier is

[1] *Op. cit.*, Fig. 3.

merely a large snow bank that was covered by rockslides. Snow banks, however, usually lie on the talus slopes, and there is no slide rock below the ice. It might be objected also that if this is glacial ice, it should have melted away. In this connection it is noteworthy that veins in the vicinity contain vugs full of ice to a depth of over three hundred feet. Also, the body of clean ice is only melting very slightly along the sides of the tunnel, although the ice in the upper part of the slide rock does melt considerably each summer.

Hurricane Basin is one of the numerous cirques of the San Juan region. The last remnants of most of the glaciers almost certainly remained in these cirques long after the end of the last glacial epoch. It is believed from the field evidence that the ice in question may be the remnant of one glacier which has survived until the present time. The covering of the glacier can probably be accounted for by the suggestion of Cross and Howe. After being covered, it seems to have resisted thawing, as it does today.